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Dynamics of Naval Ship Design: A Systems Approach

by

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BS Mathematics
United States Naval Academy, 1990

SUBMITTED TO THE DEPARTMENT OF OCEAN ENGINEERING
IN PARTIAL FULFILLMENT OF THE REQUIREMENTS FOR THE DEGREES OF

NAVAL ENGINEER
AND
MASTER OF SCIENCE IN OCEAN SYSTEMS MANAGEMENT
AT THE
MASSACHUSETTS INSTITUTE OF TECHNOLOGY

JUNE 1998

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Dynamics of Naval Ship Design: A Systems Approach

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by

Thomas A. Laverghetta

Submitted to the Department of Ocean Engineering
on May 18, 1998 in Partial Fulfillment of the Requirements for the Degrees of
Naval Engineer and Master of Science in Ocean Systems Management

ABSTRACT

The 1990 Naval Sea Systems Command Ship Design, Acquisition and Construction (DAC) Study provides a stepping stone for the implementation of improvements towards optimizing ship performance, cutting acquisition costs, and reducing design cycle time. With respect to performance, significant advances in computing power coupled with customer oriented design (QFD, AHP, evolutionary optimization, etc) provide both improvements and direct means to measure effectiveness of improvements. As for cost, implementation of world class building and design techniques (concurrent engineering, group technology, CAD/CAM/CAE, etc) coupled with higher fidelity costing methods (ACEIT, PODAC, etc) provide savings and direct measures of effectiveness. Cycle time improvements have also been implemented (IPTs, Open System Architecture, 3-D Product Models, etc). However, ship design managers have been unable to identify and quantify design process effectiveness with respect to the impact of those proposed cycle time improvements.

In order to understand the impact of cycle time improvements, it is necessary to examine the mechanisms which have lead to increased cycle time including external influences (such as increasing technological complexity and budgetary pressures), internal process delays (information flow delays and approval delays) and feedback processes (design iteration, error propagation and design change.) Modeling of such mechanisms, using the methods of System Dynamics, provides a means to study past programs (in particular, the DDG-51Destroyer program of the 1980's), and to study the anticipated savings that can be generated with the introduction of process improvements.

Of particular interest in modeling the naval ship design process with System Dynamics is the flow of design information. Traditional process analysis methods based on the design spiral represent the progression of design tasks as a linear process. However, actual design data propagation (a fundamental property resulting from the physical and architectural relationships of total ship systems) shows the process to be highly non-linear. These non-linearities are captured by system dynamics, providing a simulation tool that more fully captures the impacts of process improvements as they relate to the naval ship design process.

Thesis Supervisor: Alan J. Brown
Title: Senior Lecturer, Department of Ocean Engineering

This thesis is dedicated to my loved ones,

who make my life complete...

Kimberley, Francesca and Thomas

1 *Problem Statement*

In June 1990, under the direction of Naval Sea Systems Command (NAVSEA) Chief Engineer, RADM Roger Horne, the United States Navy undertook a program to assess the effectiveness of the naval ship design, acquisition and construction (DAC) process. The focus of this project was "to identify the critical actions necessary to improve the quality of future ship designs (i.e. meeting customer's performance requirements), to reduce ship costs (from research and development through disposal), and to reduce the cycle time required from establishment of requirements to delivery of the lead ship."[1] It was immediately recognized that naval ship acquisition is itself unique within the constrained framework of the Department of Defense (DOD) and Department of the Navy (DON) organization. In particular, Navy ships are bought in small quantities, have very long development cycles, and are extremely costly...precluding the "fly before you buy" approaches required for purchase of other weapon systems.[2] Additionally, the technical complexity of warship design has passed the point that any "one" individual can be an "expert" in all aspects of the design.[3] The resulting process is neither well documented nor well understood.

Although the purpose for the DAC program was very wide-ranging, the specific reasons prompting the DAC effort were clear: increasing naval performance requirements are resulting in increasing ship costs and increasing cycle times for delivery. The resulting "Affordability Crisis"[4] put strong pressure on the DOD to reform the acquisition process. This "Crisis" is analyzed by examining three key symptoms: increasing design cycle time, constraints leading to sub-optimal system performance, and increasing cost trends.

1.1 "Affordability Crisis"

1.1.1 Cycle Time

The time required to conceptualize, design and produce new ship designs has been increasing steadily over the years. Consider the trends for naval combatant programs shown in Figure 1. Conceptual Design time (concept design and preliminary design) is increasing at a rate of 1.5 months per year. Contract Award time (from program start through completion of contract design) is increasing at a rate of 3 months per year. Time to deliver completed ships is increasing at a rate of 5 months per year. These trends are coupled with exponentially increasing man-day efforts required to deliver ship designs (Figure 1). These trends are disturbing as they represent a barrier to providing warfighters with timely systems necessary to meet threats. The causes of these trends are numerous and will be discussed in depth in Chapter 2.

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[1] RADM Roger B. Horne, "Concept to Commissioning: Ship Design, Acquisition and Construction Process Improvement Workshop II", Richmond, VA, May 6-7, 1991.
[2] Ryan and Jons, "Improving the Ship Design, Acquisition and Construction Process", Association of Scientists and Engineers, 28th Annual Technical Symposium, April 11, 1991.
[3] Tibbitts and Keane, "Making Design Everybody's Job", Naval Engineers Journal, May 1995, page 286.
[4] Timothy P McCue, "The Dynamics of Naval Shipbuilding-a Systems Approach", Department of Ocean Engineering Thesis, Massachusetts Institute of Technology, June 1997, pages 23-44.

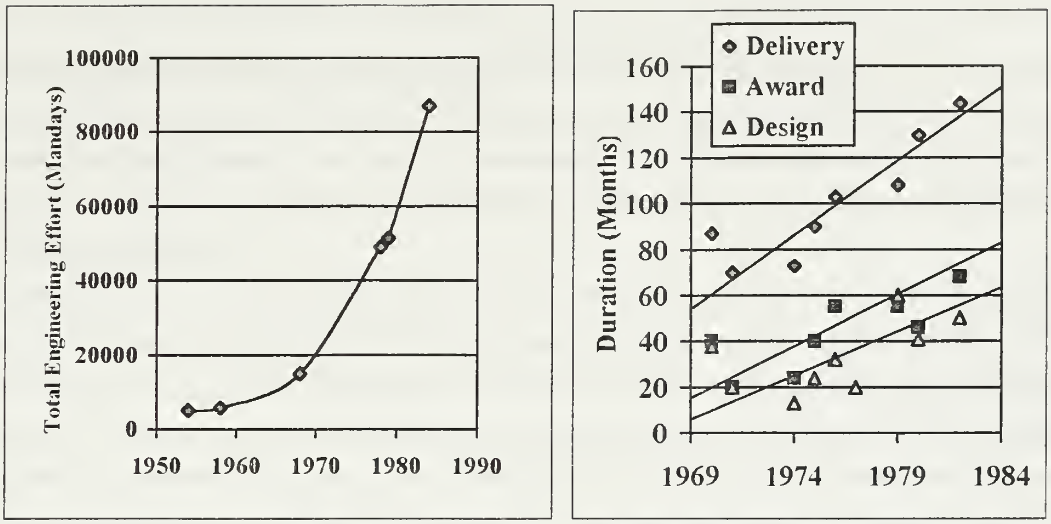

Figure 1 Combatant Cycle Time Trends[5]

The reaction to the DAC study and subsequent ship programs since the realization of these trends was significant reform and "modernization" of the design process. These reforms include revision of the basic Department of Defense (DoD) acquisition process requirements (Acquisition Reform), restructuring of the design organization to be inclusive of design agents, ship constructors and customers (IPPD/IPT and Concurrent Engineering), and application of data processing advances (SBD and 3-D Product Models).

One of the most significant process improvements has come in the form of acquisition reform. These reforms have been realized primarily through the introduction of DoDINST 5000-2R, the basic documentation of acquisition requirements.

Another method of reducing cycle time, reducing cost and improving performance is the reform of design organizations. Consider the past approaches to naval design.[6] In the 1950's, the Navy (namely the BuShips) was responsible for complete design of ships and, in many cases, the construction of those designs at naval shipyards. This approach to "in-house" design and construction was appropriate and efficient because naval ships were relatively simple (designs were consistent with World War II technologies). Naval designs that were constructed by private shipyards were the result of a largely "non-adversarial" relationship between the Navy and industry.

In 1960, the Secretary of Defense, Robert McNamara, introduced a new method of ship acquisition: Total Package Procurement (TPP). This transition was initiated to reduce costs and introduce system design of ships based on "ilities" (reliability, maintainability, survivability, etc.) Under TPP, the Navy independently performed concept formulation (CF) to validate operational requirements against potential ship designs, but the results were withheld from industry. Validated requirements (minus design suggestions) were "thrown over the wall" to industry, which performed independent contract definition (CD). CD established shipbuilder designs and solutions

[5] Ryan and Jons, "Improving the Ship Design, Acquisition and Construction Process", Association of Scientists and Engineers, 28th Annual Technical Symposium, 11 April 1991, page 10-11.
[6] Keane and Tibbitts, "A Revolution in Warship Design: Navy-Industry Integrated Product Teams", Journal of Ship Production, November 1996, page 255-259.

that optimized utilization of their construction facilities. However, the competitive environment prevented the Navy from suggesting specific design desires, despite the fact that the Navy retained responsibility for the majority of combat systems to be integrated with the design. As a result, programs such as the LHA and DD-963 produced high quality ships[7] (the result of industry optimization of construction), but resulted in large cost overruns (due to late design changes and GFE/GFI/GFM delays) and increasingly adversarial government-industry relationships.[8] As a result, TPP fell into disfavor.

The programs of the 1970's saw a return to "in-house" design efforts by the Navy. However, the decline of naval shipyards during the period of TPP resulted in the need to rely entirely on private shipyards for construction. The newly formed Naval Sea Systems Command (NAVSEA) was responsible for all phases of design through contract award. The only involvement of shipbuilders was the performance of producibility studies to suggest largely generic improvements to the design. At the completion of contract design, the design specifications were awarded as a ship design support contract to a shipyard, which allowed lead ship detailed design to begin even while construction contracts were being negotiated. The nature of the design process at this point allowed the Navy to retain significant, centralized control of the design throughout the life the acquisition. However, industry was increasingly constrained by their late participation with the design, resulting in higher construction costs.

The 1980's saw an attempt to bring shipbuilders into the process sooner. During contract design, shipyards were invited to participate in the process as observers and to introduce extensive producibility enhancements to the design. However, the potential shipbuilders could not achieve consensus on the design approach due to the substantial differences in their production methods and facilities. As such, NAVSEA designs adopted a "lowest common denominator" approach.[9] Simultaneously, system integration issues (such as introduction of the Aegis Weapons Systems on CG-47 and DDG-51 class ships) became a dominant cost and requirements drivers for ship optimization and design. The result was the introduction of collocation of design agents and increased use of computer aided design (CAD). However, these efforts fell short of their goals. Centralized design control by NAVSEA meant that collocation for a single design project might jeopardize availability of design resources for other design projects. As for CAD, attempts to use a single product model system meant translation errors and incompatibilities among as many as six different CAD systems in use by private shipyards.

The lessons of 40 years of process methods are being applied in the 1990's in an attempt to reverse the cycle time trends. With downsizing of government organizations, NAVSEA is transitioning from centralized design control to design oversight. Acquisition reform, centered on the Federal Acquisition Streamlining Act (FASA), the Federal Acquisition Reform Act (FARA), and DoD Directive 5000.1 (March 15, 1996)[10], provides a foundation from which government and industry can mutually benefit in the design process. Specifically, these reforms are

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[7] Keane and Tibbitts, "Naval Ship Design in the 21st Century", Society of Naval Architects and Marine Engineers, September 14-19 1993, page 19-3.

[8] Kenneth Cooper, Naval Ship Production: A Claim Settled and a Framework Built, Pugh-Roberts Associates, Cambridge, MA, December 6, 1980.

[9] Keane and Tibbitts, "A Revolution in Warship Design: Navy-Industry Integrated Product Teams", Journal of Ship Production, November 1996, page 257.

[10] Refer to Chapter 8.3, Glossary and Abbreviations.

changing the timing of design transition from government to industry. Traditionally, the Navy controlled the design through contract award; at which time CDRL's, military specifications, and GFE/GFM/GFI were transferred to the shipbuilder. This method left shipbuilders little room for producibility and design improvements. This approach has changed under acquisition reform. Now, design responsibility is transferred to industry as early as possible, following or even during concept design. Instead of very specific design requirements, current requests for proposal (RFP's) provide industry with performance specifications and concepts of operations aimed at communicating the nature of the problem to be solved...not the solution. The premise of reform is to allow industry to examine the needs of government and react to those needs with products not bounded by bureaucratic constraints or government design specifications. The goals are the reduction of government design and management overhead required for centralized design control and to provide industry with the incentive to seek innovative solutions that take advantage of technological and manufacturing strengths.

From a cycle time view, acquisition reform should reduce design time by setting specific schedules in the RFP for competing industries (as opposed to a single organization, the Navy, producing the design.) Thus, failure of one entity to meet the timeline will result in their loss of the contract, not the lengthening of the process. Additionally, the transfer of the design earlier in the process will result in less total information being transferred (thus, less chance of error) and open lines of communication at a time when concepts and requirements are much more negotiable.

To facilitate acquisition reform, a number of specific process innovations are being incorporated. A primary mechanism is the introduction of Integrated Product and Process Development (IPPD)/Integrated Product Teams (IPT)[11]. By IPPD/IPT, multi-disciplinary teams (representation of all potential elements of design and production with customer participation is mandatory) examine all aspects of the design process (requirements, technology alternatives, cost, ILS, manning, etc) in an environment that promotes communication. The methodology builds on the notion that no single person is the ultimate expert. Whether actual or virtual, collocation is critical to the process. Integral to IPPD/IPT is concurrent engineering[12]. Concurrent engineering seeks to consider all life-cycle aspects from the earliest design stages through manufacturing, deployment, operations and disposal. These techniques apply some basic principles: process orientation, team approach, empowerment, and open communications, parallel development and customer satisfaction. Cycle time should be shortened as critical issues for production and support as well as pro's and con's of design options are resolved early in the process, when rework and design disruption do not impact the process as greatly.

In addition to team and process approaches, the design cycle is being improved by the introduction of improved data management and analysis. The use of 3D Product Modeling[13] seeks to integrate 3D geometry, associative and parametric relationships and non-geometric information into a single model to be employed from concept design through ultimate ship disposal. The model acts as the repository for ship design and production

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[11] Simmons, Assessment of Options for Enhancing Surface Ship Acquisition, Institute for Defense Analyses, March 1996, pg. 39-40.

[12] Baum and Ramakrishnan, "Applying 3D Product modeling Technology to Shipbuilding", Marine Technology, January 1997, pg. 56.

information, and integration of logistics and life-cycle data. The model facilitates inputs and outputs for all design analysis including cost and mission effectiveness, engineering assessment and producibility. An example of a generic product model is shown in Figure 2. The model enables virtual environment design reviews, virtual shipyards, and simulation-based design. Non-geometric data is placed in a relational database system. 3D solids and surfaces are defined once with geometry modeling and parametrics and linked to multiple locations with an associativity feature. The design is stored in a heterogeneous distributed database managed by a relational database product data manager (PDM). Users establish design rules (analysis tools, design parameters, constraints) from which the design is automatically generated…when rule violations occur, the user is notified and prompted to resolve conflicts. Ultimately, a series of 3D Product Models for various ship designs could form a "Knowledge Base" from which future designs could be rapidly developed.

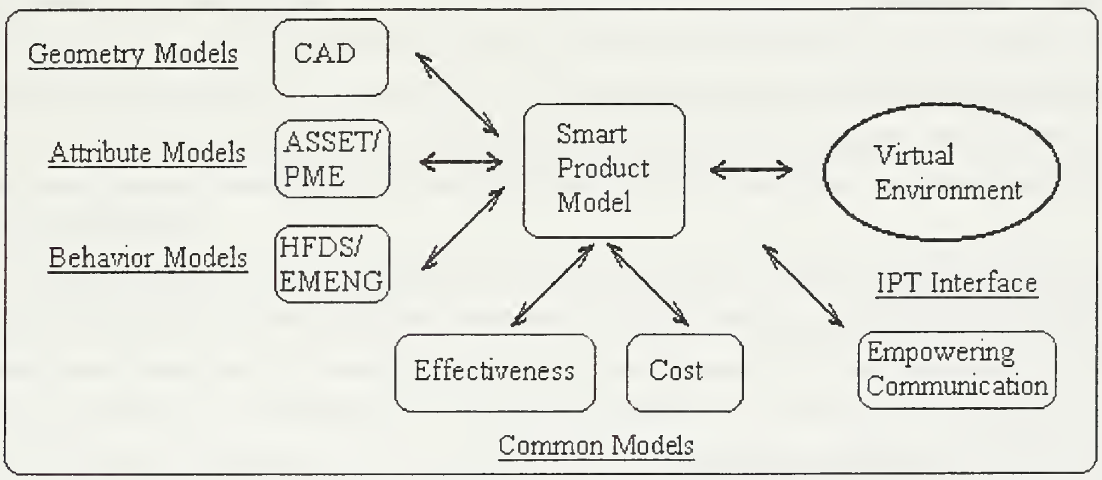

Figure 2 Generic 3D Product Model

A key feature of a 3D product model is the capability to facilitate Simulation-Based Design (SBD)[14]. SBD allows designers to assess technology insertion and design concepts in the virtual environment using Virtual Reality (VR), very large complex database systems, optimization techniques, complex data visualization, Artificial Intelligence (AI) and high performance networking. SBD realizes cost savings and performance enhancements through Modeling and Simulation (M&S) of design options (vice physical prototype construction) followed by direct extraction of production instructions (CAD/CAM/CAE[15]) from virtually tested designs. When fully realized, 3D modeling and SBD will allow dynamic model interactions of design parameters among the major design participants (Program Manager, Mission Analyst, Naval Architect, Mechanical Specialist, Purchasing Agent, Arrangement Specialist, Structural Specialist, Production Specialist, Operational Personnel, Manufacturing Specialist), and utilize these relationships to perform all required concept analysis (Mission Analysis, Mechanical System Analysis, Ship Arrangement Scenario, Operational Simulation, Coupled Hydrodynamic/Structural Analysis,

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[13] Ibid., pg. 56-65.
[14] Polini, Wooley, Butler, "Impact of Simulation-Based Design on Today's Shipbuilders", Marine Technology, January 1997, pg. 1-9.
[15] Tibbitts and Keane, "Making Design Everybody's Job", Naval Engineers Journal, May 1995, page 283.

Manufacturing Simulation, and Cost Analysis) in a virtual environment. The impact on design cycle time should be the ability to rapidly test design concepts and resolve design concerns prior to expenditure of time and resources on physical prototypes.

These reforms, though certainly more refined, are not entirely without precedence. Early design hand-off was first used during TPP. IPPD methodology was implemented during the 1970's for the FFG-7 program. Collocation and CAD technology was implemented during the DDG-51 and CG-47 programs. Total system trade-offs of cost and performance have been in use to varying degrees for several decades. Thus, the issue is now one of how much of each reform to implement, how will implementation impact ultimate performance and cost, and will external forces negate the gains brought about by reforms?

These questions are especially important in light of the long duration of design programs. For instance, typical durations for combatant ships can exceed 12 years; typical weapons system programs require 15 years for the 1st production item, and official DoD timelines (satisfying all program requirements) can exceed 22 years.[16] Those programs that have undergone the reforms of the last 10 years have yet to produce quantitative results satisfactory for analysis of improvement effectiveness: "There are good, although anecdotal, examples of this foundation actually being propagated in the field for our major programs.[17]" Is there a way to test and optimize improvements prior to implementation?

Consider the traditional project management methods listed in Table 1. These methods focus primarily on operational issues necessary to define project work structure, resource availability and requirements, and budget requirements and allocations. The methods are becoming increasingly mature with development of software suites like Microsoft Project®, At-Risk® and DoD ICOM (Input, Constraint, Output and Mechanism) packages. The approaches assume a well ordered project that progresses in well-defined stages to completion. In particular, the techniques assume a linear, or, in the case of PERT/ICOM, limited feedback process. Process improvements can be intimated and assessed by examining the risk-benefit of options or by in depth analysis of Critical Paths in the process. However, this analysis often fails to detect systemic impacts of a given process improvement or realize strategic goals for improvement processes.[18] At issue is the inability of these methods to capture decision process logic, political/social factors, workplace environment and other human factors. Additionally, their static nature cannot capture dynamics like schedule pressure, workforce experience shifts or rework issues. System dynamics can provide a methodology to capture these issues and provide the strategic analysis necessary to optimize process improvements.

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[16] Ryan and Jons, "Improving the Ship Design, Acquisition and Construction Process", Association of Scientists and Engineers, 28th Annual Technical Symposium, 11 April 1991, page 11.
[17] Dr. Paul Kaminski, Under Secretary of Defense (Acquisition and Technology), interview in Program Manager, January-February 1997, page 12.
[18] Rodrigues and Bowers, "System Dynamics in project management: a comparative analysis with traditional methods", System Dynamics Review, Volume 12 number 2, Summer 1996, page 124.

Technique/Tool	Purpose
Work Breakdown Structure (WBS)	Basic definition of the project work. Precedes the project schedule and cost estimates
Gantt Charts	Representation of project schedule, may show simple precedence relationships
Project Network Techniques: PERT, CPM, PDM, GERT	Analysis of scheduling impacts based on precedence relationships, cost estimation, resource allocation, management and risk analysis, and input-output relationships
Dynamic Strategic Planning (DSP)	Cost benefit analysis incorporating risk relationships of net present value (NPV) for options against the customer utility for those options

Table 1 Traditional Project Management Techiques[19][20]

System dynamics has been successfully applied to strategic project management for many decades. Since 1964, dynamic models have been applied to projects ranging from naval construction (1980 Litton-Ingalls Shipbuilding Litigation model) to large-scale DoD software development projects.[21] These models have accurately identified key causes of process degradation including interdependencies created by process concurrence, impacts of project scope change, and relationship of schedule pressure to productivity.

Recently, several dynamic models have been created to address the issue of strategic process improvement in private shipyards. The McCue Production Model (MIT 1997[22]) demonstrated the impact of manpower fluctuations on productivity and cost for Bath Iron Works and Ingalls Shipyard. The focus of the McCue model on manpower loading provides tremendous insight into the necessity to maintain workforce levels, even in light of short-term economic loss, in order to maintain the agility necessary to compete for emergent contracts. The Simulation of New Acquisition Processes (SNAP) program (DDI 1997[23]) bridges the gap between system dynamics models and operational methods by demonstrating the dynamic flow of shipyard work against changing resource availability, personnel productivity and schedule pressure. The model is especially useful because it incorporates ship work breakdown structures familiar to shipyard managers…thus, instilling a high level of confidence in the results of process analysis. Models are also being applied to other naval process issues such as operations and support costs.

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[19] Ibid., page 121.

[20] Richard de Neufville, Applied Systems Analysis: Engineering Planning and Technology Management, McGraw-Hill Inc, 1990.

[21] Rodrigues and Bowers, "System Dynamics in project management: a comparative analysis with traditional methods", System Dynamics Review, Volume 12 number 2, Summer 1996, page 128.

[22] Timothy McCue, "The Dynamics of Naval Shipbuilding-a Systems Approach", Thesis for Massachusetts Institute of Technology, June 1997.

[23] Alfeld, Wilkins and Pilliod. "The Virtual Shipyard: A Simulation Model of the Shipbuilding Process", The Society of Naval Architects and Marine Engineers, April 21-23, 1997.

naval forces requirements and cost optimization[24], and the interaction of DoD acquisition programs[25]. The effect of this effort is the increased application of system dynamics as a tool to assess and optimize process improvements from the strategic level. However, there has not yet been a significant move to apply simulation models to the design process.

A. Unacceptable cycle time trends have lead design managers to implement many process improvements aimed at reversing these trends. However, insufficient time has passed to determine the full effectiveness of these improvements.

B. Given the duration of the design process and the lack of fidelity in traditional project management methods to strategically analyze effectiveness, system dynamics should be applied to naval design to provide a means of:

1. ***Analyzing the causes of cycle time growth***
2. ***"Gaming" potential process changes to determine effectiveness and relative risks.***

1.1.2 Requirements and Design Performance

Like the problem of cycle time trends, performance issues are an increasing concern to warfighters and designers alike. Requirements assessment is seeing significant introduction of new techniques to assess risk and effectiveness long before the laying of steel or the programming of weapons software.

"The modern warship (is the) most complex machine devised by man."[26] Their complexity crosses every discipline of modern engineering and physics from fluid dynamics to computer network design to nuclear engineering. The complexity is further increased by the dynamic interactions of these unique disciplines resulting in the integration of a single system. The ad hoc optimization process, which creates this system, is based on compromise and trade-off of various requirements and system options. However, with ever growing design complexity comes an increasingly unanswerable question: has the optimal solution been achieved? Resoundingly, the answer is no, and the difficulty is translating operationally required mission effectiveness into optimized design parameters.

Until recently, mission effectiveness was defined qualitatively. Performance requirements were provided to designers, but the operators had few means to quantitatively assess the effectiveness of such requirements, and designers were provided little room or guidance to trade requirements and cost. For example, requirements would

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[24] Towles, Rocholl, Jeffers and Platt, "Force Affordability Modeling: the Dynamic Investment Balance Simulation (DIBS)", presentation to Naval Surface Warfare Center Carderock Division, Bethesda, MD, April 15, 1997.
[25] Towles, Rocholl, Jones, Jeffers and Platt, "System Wormhole Analysis Tool (SWAT): a Simulation Based Acquisition Initiative," presentation to Naval Surface Warfare Center Carderock Division, Bethesda, MD, October 27, 1997.
[26] Gale and Scott, "Early Stage Ship Design Seminar", Society of Naval Architects and Marine Engineers, October 1995.

state "carry out anti-submarine operations in the North Atlantic" or "maintain X knots in sea state 5."[27] Such statements are misleading to both requirements setters and designers. The first, more general statement, does not indicate any level of trade-off or even a notion of what "anti-submarine operations" might entail. The designer is forced to assume an engineering definition and may inevitably misinterpret the operators' true intentions. The second, more specific requirement removes all potential for trade-off against other variables, and does not allow alternate solutions to the problem. Under these circumstances, designers are often detached from customers (operators), and are forced to make critical decisions without explicit feedback until the system is operational.

For the designers, there is a lack of clarity as to who the customer is:[28] the operator, the ship builder or just the next designer in the design chain. There is a tendency to under-fund R&D efforts and requirements setting processes which would allow both designers and operators to reach better optimized solutions. These factors combine to add confusion and delays to the requirements setting process.

Requirements setters within the operating forces of the Navy (OPNAV), are frequently focused on details and fail to communicate "big picture" needs. Turnover is also rapid and OPNAV personnel may be transferred before they understand and appreciate the problem.[29] Additionally, the customer lacks understanding of the ship design process. Specifically, the fleet operators aren't able to understand how specific requests for performance translate into design trade-offs.[30]

When performance changes are requested (due primarily to out-of phase development programs and conflicting requirements at various stages of design definition[31]), the resulting disruption to the design process is significant. For instance, Table 2 shows how design priorities changed over the course of the DDG-51 preliminary design effort. Customer priority changes, particularly with respect to energy conservation, resulted in a large design effort (culminating in several design variants and two independent design studies[32]) to analyze designs which incorporated the RACER (Rankine Cycle Energy Recovery) propulsion system. However, total ship system impacts of RACER and program risks related to the RACER R&D schedule (not in phase with DDG-51) ultimately resulted in cancellation of the RACER integration with DDG-51 and a further realignment of performance priorities (highest to lowest) in the DDG-51 contract phase to[33]:

a. Combat system capability
b. Speed and endurance
c. Survivability
d. Habitability

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27 David Brown, "Naval Architecture", Naval Engineers Journal, January 1993, page 43.
28 Ibid. page 2-22.
29 Roger Horne, Improving the Ship Design, Acquisition and Construction Process: Strategic Plan, Naval Sea Systems Command, Washington DC, June 1991, page 2-20.
30 Ibid. page 2-21.
31 Ibid. page 2-21.
32 Andy Summers, , DDG 51 Guided Missile Destroyer Preliminary Design History, Naval Sea Systems Command, June 1984, page B-1.
33 Andy Summers, DDG 51 Guided Missile Destroyer Contract Design History, Naval Sea Systems Command, June 1987, page 3-1.

e. Design flexibility and growth potential

These changes lead to further delays and generated additional iterations of the DDG-51 design.[34] Changing priorities, unclear requirements relative to total system impacts and out of phase development programs generate design effort.

Attribute	Priority at Start	Priority at Finish
Combat Capability	High	High
Acquisition Cost	High	Medium High
Operability	Medium High	Medium
Passive Survivability	Medium High	High
Energy Conservation	Medium High	High
Future Growth Flexibility	Medium High	Low
Active Survivability	Medium	Medium High
Ship Displacement	Medium	High
Manning Reductions	Medium	Low
Habitability	Low	Medium High
Minimum Risk	Low	Low
Standardization	Low	Low

Table 2 Preliminary Design Priorities at Beginning and End of Design Phase[35]

As a result of the noted shortcomings (dating back to the late 1980's), the DAC study[36] and other process improvement efforts such as Secretary of the Navy Instruction 5000.2B[37], the requirements process now institutes improved performance assessment mechanisms. These mechanisms provide for structured input of requirements, assessment of engineering solutions with respect to those requirements and feedback from operators regarding system solution options. Some of these improved methods include Quality Function Deployment (QFD), Analytical Hierarchy Process (AHP), and Genetic Algorithms.[38]

The QFD method, which was devised by a shipyard in Kobe, Japan to address the same problems relative to its customers, provides a structured process of taking customer needs (stated in the subjective, qualitative and non-technical "voice of the customer") and translating those needs into "corporate language" (quantitative and technical

[34] Verne Stortz, "DDG-51 Cost Estimate Log", Naval Surface Warfare Center Carderock Division, Bethesda, MD. October 1984.
[35] Andy Summers, , DDG 51 Guided Missile Destroyer Preliminary Design History, Naval Sea Systems Command, June 1984, page 3-1 and 3-3.
[36] Ibid. page 2-16.
[37] John Dalton, Implementation of Mandatory Procedures for Major and Non-Major Defense Acquisition Programs and Major and Non-Major Information Technology Acquisition Programs (SECNAVINST 5000.2B), Department of the Navy, Washington DC, December 6, 1996, Appendix II.
[38] Defense Acquisition Deskbook Joint Program Office, "Defense Acquisition Deskbook Version 2.3.101", Wright-Patterson Air Force Base, Ohio, March 31, 1998.

parameters required by designers.)[39] The customer traits are commonly referred to as Measures of Effectiveness (MOEs) while design performance attributes are Measures of Performance (MOPs). QFD provides a qualitative mapping from MOEs to MOPs. The two "languages" are translated via a matrix referred to as the "House of Quality" (see Figure 3 below.) The mapping highlights synergies and conflicts between design options and competing customer requirements. As a result, customers and designers can visualize design trade-offs and propose alternative solutions. The process is iterative and its greatest use is as a means to facilitate communication between customers and engineers throughout the design process. The method has proven useful in Navy programs ranging from the Joint Advanced Strike technology (JAST) program to the Next Generation Carrier Program (CVX.)[40]

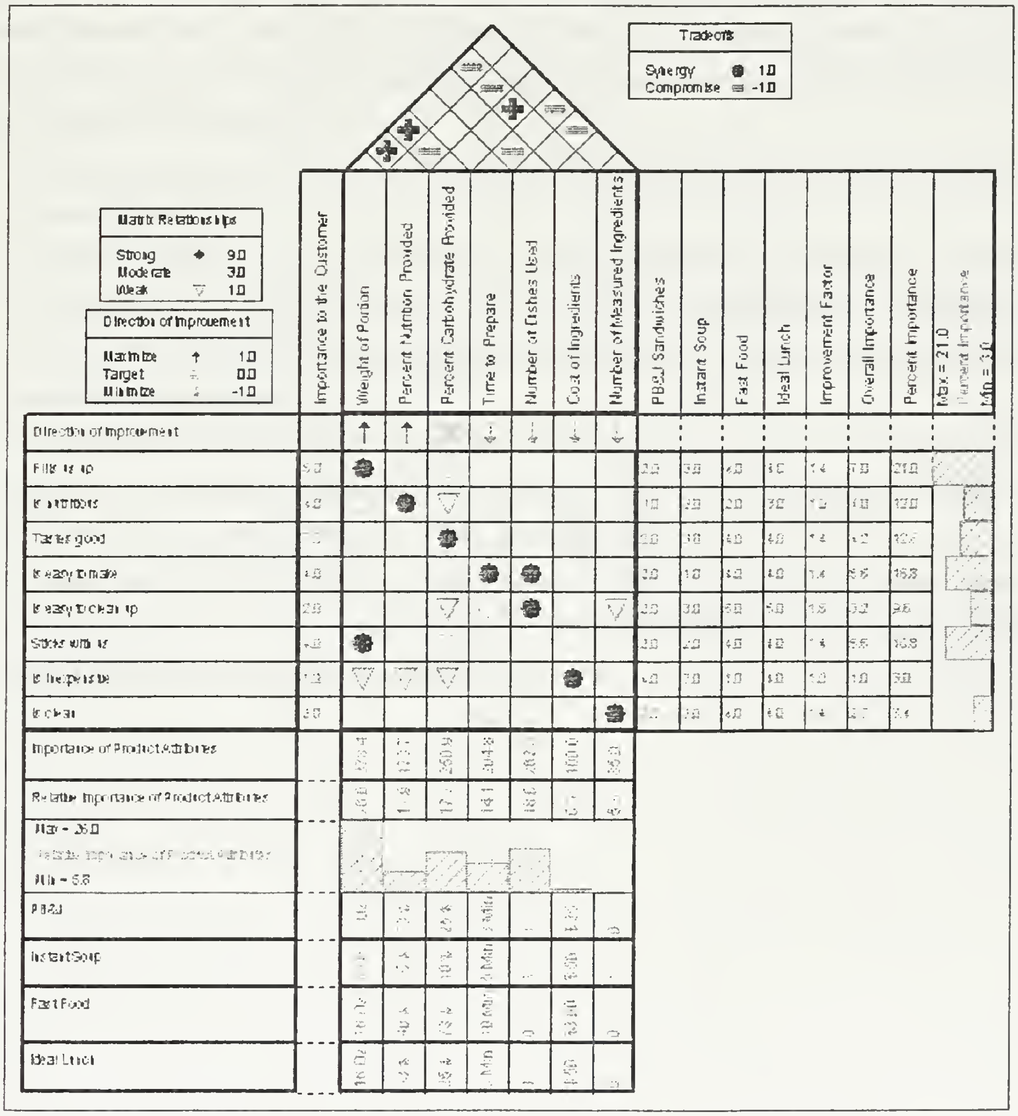

Figure 3 Quality Function Deployment "House of Quality"[41]

[39] Tibbitts and Keane, "Making Design Everybody's Job", Naval Engineers Journal, May 1995, page 287.
[40] Ibid. page 287.
[41] International TechneGroup Incorporated (ITI), http://www.iti-oh.com/cppd/qfd/qsoft.htm.

Whereas QFD is a qualitative method of communicating performance attributes. AHP aims to quantify performance attributes in a manner which allows designers to search a boarder solution space while still meeting fundamental performance needs. Specifically, requirement setters and engineers establish a well defined, mutually agreed to set of performance attributes and the quantifiable values of those attributes. The requirement setters then weight the attributes through a series of pair-wise comparisons. The result of such comparison is a vector of weighting factors relating the "goodness" of each attribute against another. Thus, engineers can explore the entire solution space and determine the optimization of customer needs within that space. An example of this method of has been to quantify variables ranging from producibility of ships to life-cycle cost to combat performance.[42] In this example, subject-matter experts were questioned regarding a number of performance attributes. Those attributes as well as the weighting factors for a number of ship types (Destroyers and Carriers) are shown in Table 3 below. Using the AHP method, a designer would

a. measure the attribute values (MOPs) for generated system designs (such as sustained speed is 20.1 knots or 25.6 knots),
b. normalize the MOPs against previously agreed goal and threshold values (such as 20.1 is 0.014 and 25.6 is 0.80 to a goal of 27 knots and a threshold of 20 knots) or ask customers to re-evaluate design attributes directly by additional pair-wise comparison (to generate a summary values from 0 to 1 for a parameter like modularity),
c. multiply normalized MOPs times the weightings for each parameter which in turn generates top-level MOEs for each attribute category (such as 0.8 times 0.3174 is 0.2539 for speed and the total of all MOPs for Operational Capability adding to a value such as 0.112),
d. then sum the MOEs to determine an Overall Measure of Effectiveness (OMOE) value for each design (such as design 1 is 0.23 and design 2 is 0.45)...the highest OMOE design is the optimal customer directed design relative to the other scored designs.

[42] Wilkins, Kraine and Thompson, "Evaluating the Producibility of Ship Design Alternatives", Journal of Ship Production, August 1993, page196-201.

Ship Performance Criteria	DD	CVN
Operational Capability	0.5971	.07009
Payload Carrying Capacity	0.1293	0.0666
Payload Effectiveness	0.3030	0.3252
Mobility	0.1194	0.0362
Speed	0.3174	0.4444
Endurance	0.5110	0.4444
Maneuverability	0.1716	0.1111
Availability	0.2516	0.1814
Survivability	0.1967	0.3907
Operational Efficiency	0.2106	0.2020
Manning	0.3768	0.7142
Habitability	0.2066	0.1429
Safety	0.4166	0.1429
Future Growth Margin	0.1924	0.0971
Weight Margin	0.2460	0.3214
KG Margin	0.1582	0.3214
Volume Margin (density)	0.2060	0.3214
Modularity	0.3898	0.0357

Table 3 Ship Performance Weighed by Analytical Hierarchy Process Methodology[43]

The previous methods provide both a means to define customer needs relative to designer attributes and trade-off specific designs against each other in a structured environment. Genetic algorithms provide the final step in system performance optimization by systematically enabling designers to search a highly non-linear design space for the overall optimal solution relative to the user defined OMOE. Specifically, genetic algorithms take a series of design parameters or "genetic materials" (such as LBP, a series of discrete combat systems suites or various hull material mixes), generate designs from those genes, assess the OMOEs for the resulting designs, "mate" the designs with each other to generate new "generations" of designs, introduces "mutations" to a limited number of the genes in each generation, and continues the process until the design no longer improves or "evolves." Traditional AoA methodology derives optimization of the design space through directed exploration of an overly large number of design alternatives. Such exploration is only possible using design synthesis tools like the Advanced Surface Ship Evaluation Tool (ASSET). Such tools allow a small team of designers to rapidly develop and balance a large number of ship alternatives. For example, the current CVX program is exploring design in three stages (airwing size and composition alternatives, propulsion alternatives and system alternatives) with as many as 30 designs per stage.

[43] Ibid. page 200.

Past explorations using design synthesis programs like DD08 and ASSET have generated as many as 1000 different ship designs in an effort to ensure an optimum solution.[44] However, even with synthesis tools, much the design work is still manual, such as topside arrangement of a combat system suite or flight deck design in a CAD environment. As such, designers still must approach the analysis of the solution space as an "experimental design", which is linear. Given the increasing complexity of current designs and the time required to generate a single design, it is necessary to have a method like genetic algorithms to ensure not only local, but global optimization of the solution. As the design space is highly non-linear, sub-optimized solutions are often pursued (see Figure 4.) Genetic algorithms can avoid such occurrences by not focusing the search in a linear manner (as with by a staged AoA approach) but evolving beyond local optima to achieve the peak solution. The use of such approaches are proving successful both in academic pursuits of design (Mark Thomas and Allan Andrew theses) and active programs (Joint Strike Fighter Program use of SNAP[45]).

Performance and the systematic optimization of performance is a key concern to operators and designers alike. However, the customer oriented methods of QFD and AHP, along with the optimization techniques of AHP and Genetic Algorithms, provide means to overcome past concerns. The Navy is beginning to apply these techniques with success…but the question remains whether these successes are enhancements to design performance alone, or whether the dynamic impacts of performance enhancements will result in cost and cycle time growth. These impacts will be addressed further in Chapter 2.

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[44] Myron Ricketts, Manual for Naval Surface Ship Design Technical Practices, Naval Sea Systems Command, Washington DC, 1980, Volume 1, page 5-35.
[45] Alfeld and Shepard, "SNAP-Simulating New Acquisition Processes", CAIV Workshop, Decision Dynamics INC, 11-12 July 1997.

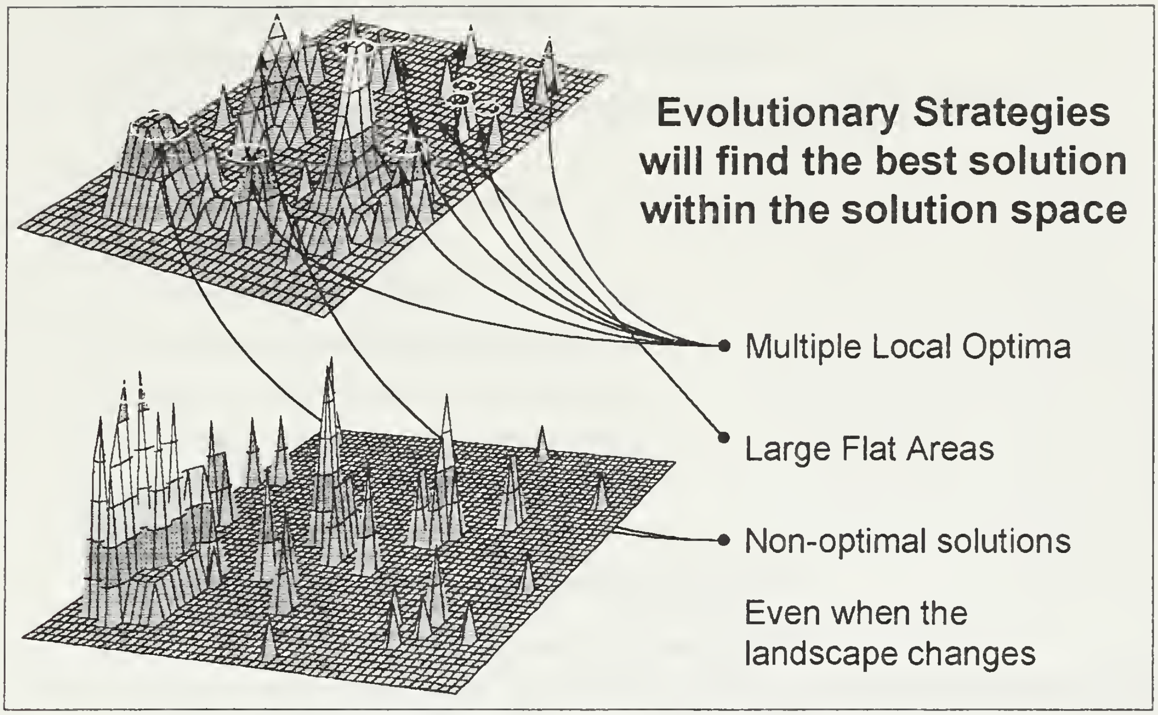

Figure 4 Optimization and Genetic Algorithms[46]

1.1.3 Cost

In addition to the need to achieve required performance within a constrained schedule, modern warships must also be cost effective. The cost of ships has been steadily increasing, well above obvious increases due to inflation. The DAC study shows an alarming growth trend. Average combatant ship acquisition cost in equivalent dollars (normalized in the study to FY90) has increased linearly over 800% per vessel over a thirty year period.[47] This trend alone, has represented the single most critical factor driving the need for acquisition reform. As such, strategic cost analysis and cost analysis tools have received significant emphasis in the last decade.

There are a multitude of reasons for this trend. Consider the list of cost roadblocks disclosed during the DAC Study (Table 4). Many of the listed concerns (construction delays from late design changes and GFE/GFI, lack of shipbuilder producibility inputs, and failure to fully explore design options prior to preliminary and contract design) have already been noted as equal problems related to schedule and performance.

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[46] Ibid.

[47] Ryan and Jons, "Improving the Ship Design, Acquisition and Construction Process", Association of Scientists and Engineers, 28th Annual Technical Symposium, 11 April 1991, page 11.

- Too many changes after contract award
- Requirements setting without rigorous cost-benefit analysis
- Lack of cost awareness or cost analysis capability organic to the design community
- Inefficient shipbuilding practices
- Awards based on unrealistic, low bids
- Late delivery of GFI/GFE
- Labor intensive ship designs
- Insufficient production and future growth margins
- Lack of system architecture to accept change
- Out dated specifications, practices and margins
- Under-funding of Concept Design Phases
- Increasing complexity and cost of combat systems
- Excessive costs associated with programmatic documentation

Table 4 DAC Study Cost Roadblocks[48]

The most noteworthy cause of cost growth in naval design is the failure to leverage the relationship between cost and time. Consider Figure 5. In the early stages of design, decisions are made that define the general characteristics of the ship. Those initial decisions have not traditionally incurred large costs (i.e. concept design funding has been limited), but they do produce future costs by the definition of specific ship design choices. For example, the result of concept design may indicate the desired vessel to be a destroyer, approximately 465 ft long, 6800 lton light ship displacement, capable of 30 kts sustained speed using 4 LM-2500 engines, with 350 personnel, 1 5"/54 DP Gun, 96 VLS cells and the Aegis weapon system centered around the SPY-1D radar system. The description does not provide enough detail to construct a ship, but it is good enough to estimate acquisition cost to within 80% probability of accuracy. The reason is that historically, the above factors will result in 80% of the total cost of the ship. As the design process matures, greater design detail is expressed, incurring greater costs through increased design effort and, ultimately, construction. However, this detail does not create substantial changes in end cost. For our example, later design stages may change the length to 466 ft, the deckhouse may be constructed from steel vice aluminum, and the scantlings in the double bottom may be increased for increased defense from underwater explosions. However, these changes will not result in significant cost changes beyond the initial estimate. This fact will be increasingly important with respect to combat system impacts on cost (discussed below). Thus, the levels of cost "lock-in" and cost incurred are inversely proportional.

[48] Ibid., page 14.

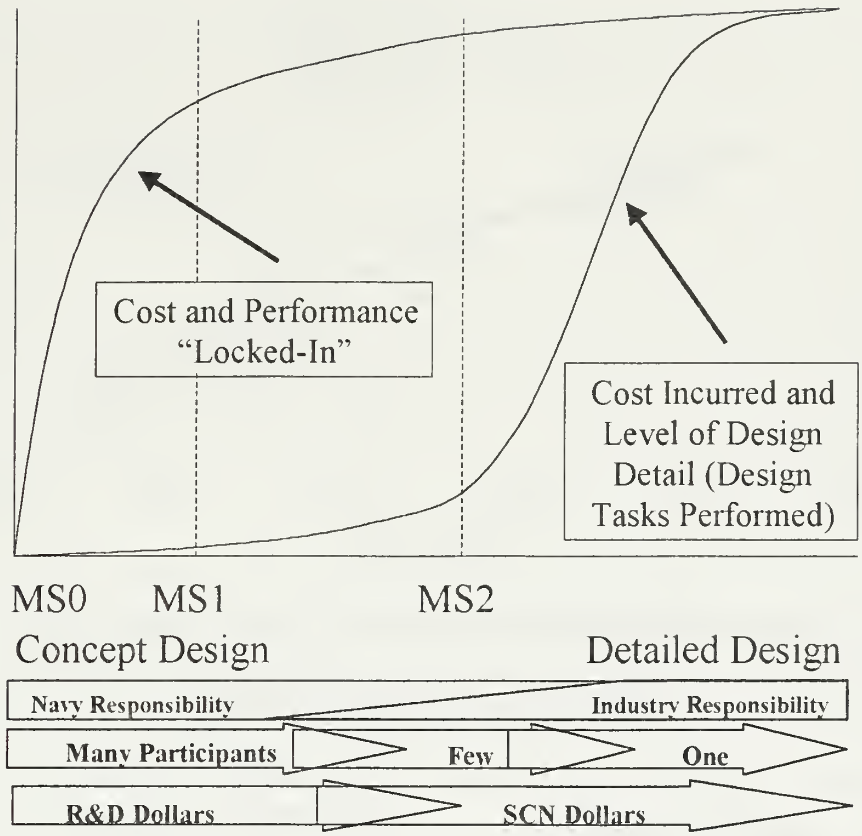

Figure 5 Key Transitions in the Design Process

This relationship can be further demonstrated in the methods of managing weight and weight based costs during the design process. Consider a typical trend for weight and KG demonstrated in Figure 6. Despite short-term fluctuations, the overall trend (indicated by the included trend line) is that of exponentially decaying growth towards a final value, namely, the light ship weight at launch. It is necessary that convergent behavior in all aspects of the naval design exist. Otherwise, it would be impossible to determine whether the completed ship would function desirably as a system (i.e. float and float upright.) It is likewise expected that the values for properties such as weight, KG, electrical load, etc. at the beginning of contract design will be exceeded during detailed design; and even further exceeded during the expected life of the ship. As the design matures, assumptions regarding system weights, locations, scale, etc, are refined. To err conservatively, the assumptions are adjusted with margins to reflect potential growth. Margins are added to those system values (weight, KG, powering, etc.) that are critical to ship performance. Table 5 shows weight and KG margins used for the design naval surface combatants. These margins are considered the minimum additional weight or moment-arm that should be included in a design to account for uncertainty in assumptions. At the conclusion of a design phase, the design managers may choose to reduce or eliminate margins from previous stages as the level of confidence in the current design values (reflective of the level of detail achieved) is increased. This trend is displayed for the DDG-51 program in Figure 7.

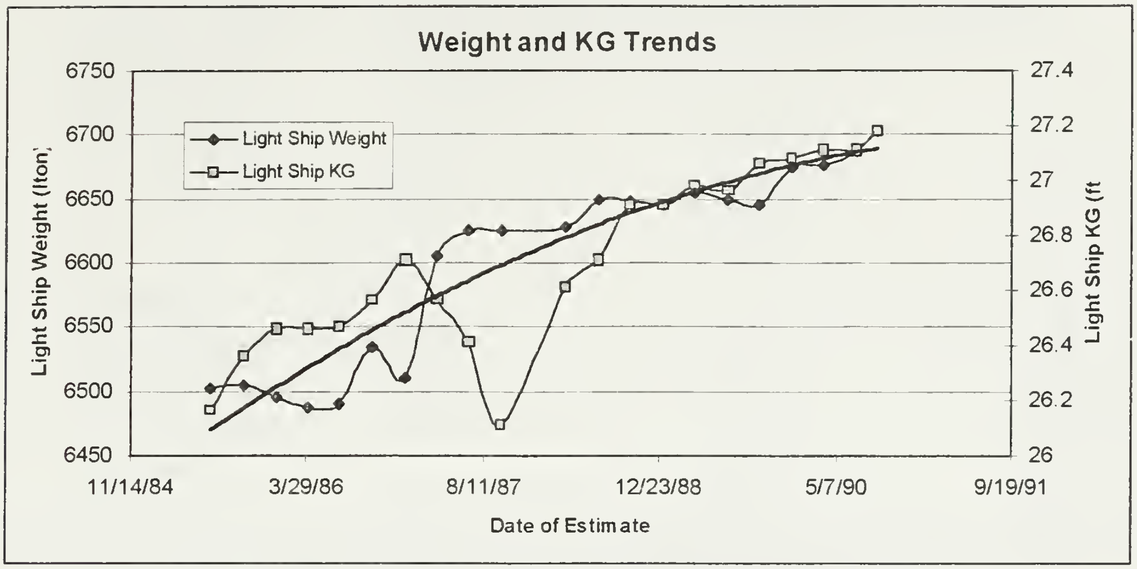

Figure 6 DDG-51 Contract - Detailed Design Weight and KG Trends[49]

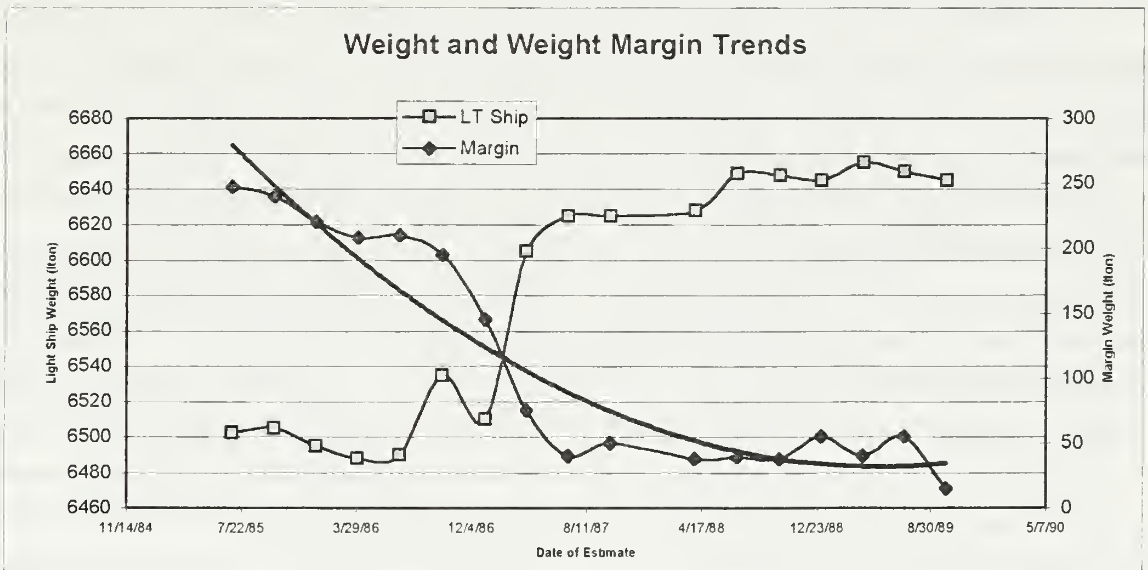

Figure 7 DDG-51 Detailed Design Weight Margin Trends[50]

[49] Mike Jeffers, Interview at Naval Surface Warfare Center Carderock Division, Bethesda, MD, November 12, 1997.
[50] Ibid.

Weight Margin	Mean %	Mean Plus Standard Deviation %
PD/CD Margin	0.83	4.36
D&B Margin	1.71	5.29
C. MOD Margin	0.33	1.43
GFM Margin	0.33	1.20
		12.28%
KG Margin		
PD/CD Margin	2.67	6.09
D&B Margin	1.87	4.97
C. MOD Margin	0.18	1.12
GFM Margin	0	0.34
		12.52%

Table 5 NAVSEA Design and Life Cycle Margins[51]

As regards cost, it is important to consider the trends of design resulting from margins and convergent design because the traditional methods of determining cost rely heavily on weight and major system selections. Specifically, traditional acquisition cost estimates during design are determined using parametric analysis of weights (from Ships Work Breakdown Structure (SWBS) groups) for similar ship types of the past. Table 7 shows top-level SWBS groups considered in early ship design and cost analysis. The SWBS groups represent an accounting method that provides means to estimate features of the ship (such as weights and distribution of weights for structures, support systems, etc) that cannot be explicitly defined during early design. Cost estimating relationships (CER's) are applied to the SWBS weights to determine cost estimates. These weight-based cost estimates may be adjusted for specific shipyards, known system costs, learning curves associated with multi-year contracts (Figure 9), and other reasonable cost impacts. Generally, the result of the estimates determined in this manner should follow behavior similar to the weight behavior of Figure 6, i.e. the estimate should converge. During later design stages, small transfers of weight from one SWBS group to another may result in substantial first order cost impacts. These impacts can be forecasted early in the design process through sensitivity analysis of the parametrics (Table 6.) However, the second order cost impacts due to disruption, transitions within SWBS groups and multi-ship schedule shifts are not disclosed with weight-based costing[52]. Although these impacts are usually within 20% of the parametrically determined values, they can grow to levels of well over the initial cost.[53] That has been a criticism of such cost methods. There is a need to improve the methodology of weight-based costing to be responsive to second order effects, or new methods must be used.

[51] Reuven Leopold, Manual for Naval Surface Ship Design Technical Practices, Naval Sea Systems Command, Washington DC, 1978, page 4-157

[52] Kenneth Cooper, Naval Ship Production: A Claim Settled and a Framework Built, Pugh-Roberts Associates, Cambridge, MA, December 6, 1980.

[53] Prof. Alan Brown, interview May 11, 1998, Massachusetts Institute of Technology, Cambridge, MA.

Ship Work Breakdown Structure	Program Cost (FY 83 $/lton)
100 Structure	17,500
200 Propulsion	110,800
300 Electric	180,200
400 Command	46,300
500 Auxiliary	80,800
600 Outfit	78,500
700 Armament	16,000

Table 6 Cost/Weight Sensitivity[54]

SWBS	Description	SWBS	Description
100	Hull Structures	500	Auxiliary Systems, General
110	Shell and Supporting Structure	510	Climate Control
120	Hull Structural Bulkheads	520	Sea Water Systems
130	Hull Decks	530	Fresh Water Systems
140	Hull Platforms And Flats	540	Fuels and Lubricants,Handling and Storage
150	Deck House Structure	550	Air,Gas and Misc Fluid Systems
160	Special Structures	560	Ship Control Systems
170	Masts, Kingposts, And Service Platforms	570	Underway Replenishment Systems
180	Foundations	580	Mechanical Handling Systems
190	Special Purpose Systems	590	Special Purpose Systems
200	Propulsion Plant	600	Outfit and Furnishings,General
210	Energy Generating System (Nuclear)	610	Ship Fittings
220	Energy Generating System (Nonnuc)	620	Hull Compartmentation
230	Propulsion Units	630	Preservatives and Coverings
240	Transmission and Propulsor Systems	640	Living Spaces
250	Propulsion Support Systems (Except Fuel and Lube Oil)	650	Service Spaces
260	Propulsion Support Systems (Fuel and Lube Oil)	660	Working Spaces
290	Special Purpose Systems	670	Stowage Spaces
		690	Special Purpose Systems
300	Electric Plant, General	700	Armament
310	Electric Power Generation	710	Guns and Ammunition
320	Power Distribution Systems	720	Missles and Rockets
330	Lighting System	730	Mines
340	Power Generation Support Systems	740	Depth Charges
390	Special Purpose Systems	750	Torpedoes
		760	Small Arms and Pyrotechnics
		770	Cargo Munitions
		780	Aircraft Related Weapons
		790	Special Purpose Systems
400	Command and Surveillance	800	Engineering
410	Command and Control Systems	812	Change Proposals, Scoping, Checking
420	Navigation Systems	813	Planning & Production Control
430	Interior Communications	831	Construction Drawings
440	Exterior Communications	835	Engineering Calculations
450	Surface Surveillance Systems (Radar)	838	Design/Engineering Liason
460	Underwater Surveillance Systems	839	Lofting
470	Countermeasures	841	Tests & Inspections, Criteria & Procedures
480	Fire Control Systems	844	Combat Systems Checkout Procedures
490	Special Purpose Systems	850	ILS Engineering
		897	Project Management

Table 7 Ships Work Breakdown Structure

[54] Hope and Stortz, "Warships and Cost Constraints", Naval Engineers Journal, March 1986, page 45.

Another particular concern is the increased dominance of combat system costs compared to overall ship costs. Consider the trends shown in Figure 8. The combat system cost fraction for both combatants and amphibious ships are steadily increasing. In the years during and following World War II, combat systems consisted primary of high density, heavy-weight gun systems. The primary integration issues (and thus cost and system trade-offs) were gun placement and provision for adequate displacement to support those guns and their ammunition. The USS Atlanta (CL-51) is representative of such designs (Table 8.) Its combat system suite is consistent with other World War II designs: low cost, low technology, and highly redundant. The gun systems are manpower intensive, but the manpower is dominated by low skill, low cost gun handlers. The resulting ship has a relatively small fraction of acquisition cost dedicated to combat systems (less than 40%), and operations and support costs are dedicated to supporting a young, unskilled labor force. An intermediate generation of combatant ships (represented by the DD-963 class) falls in the transition period for acquisition and design methodologies, TPP. The combat systems are more complex and more expensive as a fraction of the total cost, which also shows an increasing trend (Figure 9.) A ship designed by shipbuilders (Litton-Ingles Shipbuilding), it has greater total volume to accommodate improved producibility and acceptance of future system upgrades. As a result of these improvements and if not for the government induced cost over-runs (Chapter 1.1.1), the ship acquisition cost may have been comparable to the CL-51. Manpower is increasingly skilled in electronics, sensor management and other specialty skills. As a result, the ship is not only increasing in combat systems cost, but also operations and support costs, which are dedicated to system maintenance and manpower training. The final generation of the combatant (DDG-51) is the epitome of current design and cost trends. The combat system is a very large fraction of acquisition cost. Artificial constraints imposed on displacement and length, coupled with requirements to elevate large sensors on the superstructure, result in a "beamy", dense ship that poorly incorporates producibility features.[55] Thus, acquisition costs are undesirably high. Crew growth coupled with further complexities in the combat system suite require the most highly skilled crews to operate and maintain. The result of these factors: DDG-51 has pushed the combat system cost and total acquisition cost trend to a critical level, and operations and support costs have exceeded reasonable budgetary levels.

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[55] Philip Sims, "Ship Impacts Studies", Naval Engineers Journal, May 1993, page 87.

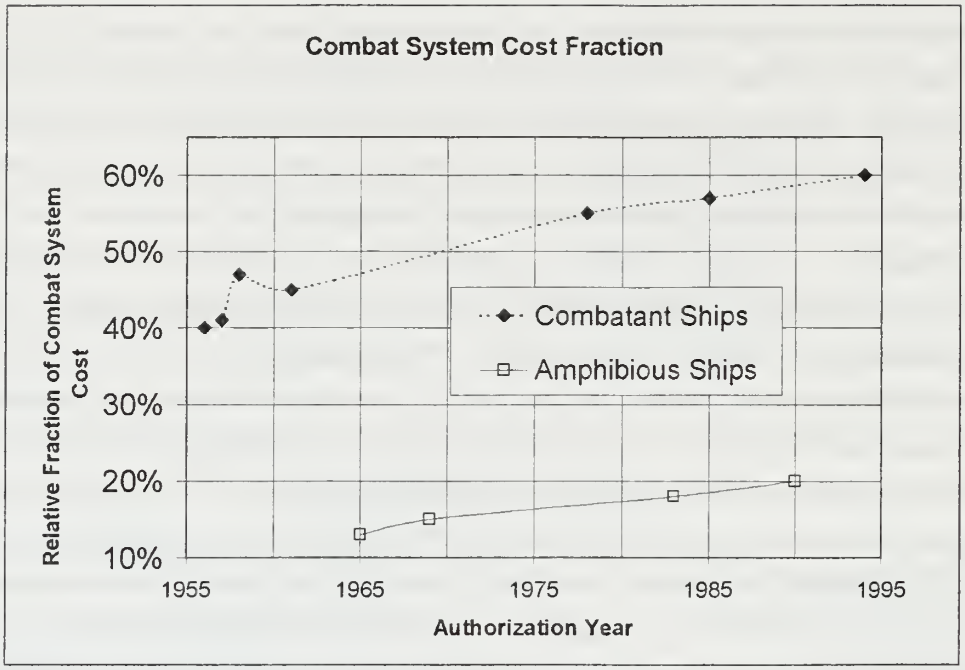

Figure 8 Combat System Cost Trends[56]

Ship	Atlanta CL-51	Spruance DD-963	Arleigh Burke DDG-51
Design Date	1938	1969	1982
Full Load (lton)	8440	7800	8300
LBP (ft)	530	529	466
Beam (ft)	53	55	59
D10 (ft)	33.2	42	42
Volume (ft^3)	700,000	1,030,000	971,000
Vol to Wt (ft^3/lton)	82.9	132.1	117.0
Crew	626	276	318
Combat Cost Fraction	40	47	57
Strike Weapons	8 x 5"/38	2 x 5"/54 Harpoon Missiles	1 x 5"/54 Tomahawk Missiles
AAW	40 & 20 mm Guns	NSSM	SM-2
Sensors	Small radars Small sonar Optical	Medium radars Big sonars Towed array	Big radar Big sonar Towed array

Table 8 Comparison of Combatants over Time[57]

[56] RADM Roger B. Horne, "Concept to Commissioning, Improving the Ship Design, Acquisition and Construction Process: Strategic Plan", Naval Sea Systems Command, Washington, DC, June 1991.
[57] Philip Sims, "Ship Impacts Studies", Naval Engineers Journal, May 1993, page 91.

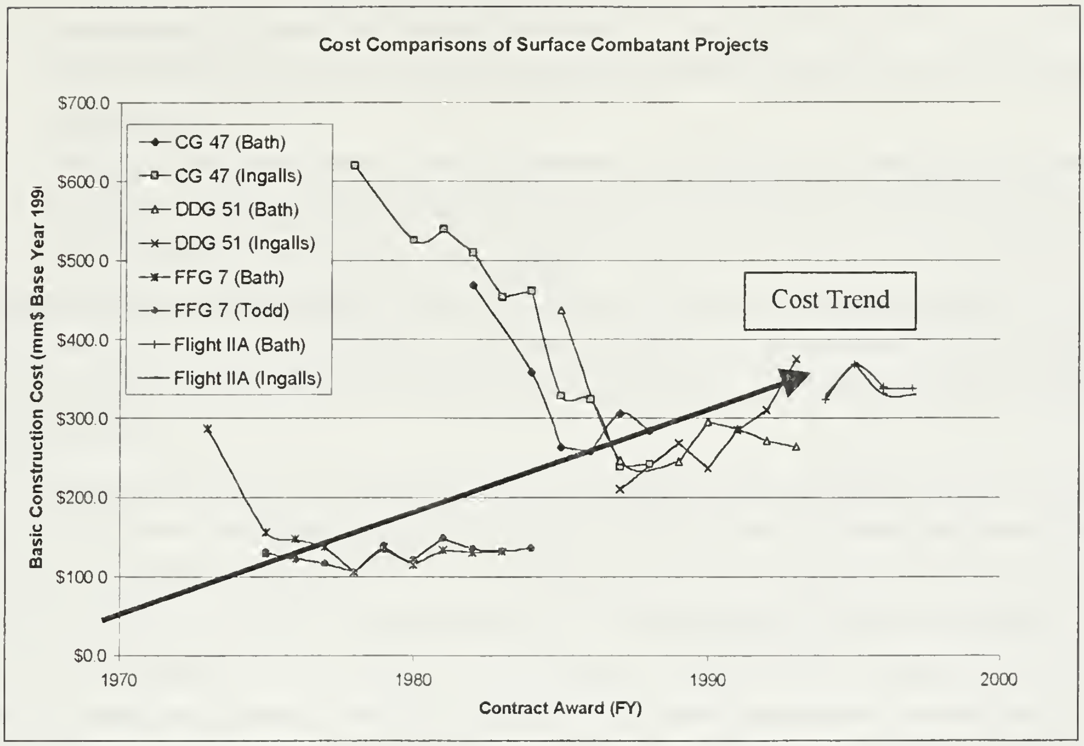

Figure 9 Basic Cost of Construction Trends for Surface Combatants[58]

As a result of these trends, many cost control programs have been implemented. First, weight-based costing has evolved greater fidelity. The ACEIT (Automated Cost Estimating Integrated Tool) cost program is a Joint Service system providing a suite of costing tools designed to assist analysts in arriving at cost estimates, conducting "what-if?" studies, developing cost proposals and evaluations, conducting risk and uncertainty analysis, and developing CER's. The program, developed and maintained by Tecolote Research Inc., provides many improvements over traditional weight-based approaches including[59]:

- User defined WBS with capability to build one or more default WBS and associated definitions,
- Ability of users to enter their own cost equations, access a built-in Methodology Knowledge Base, search for analogous data, or create CER's,
- The calculation of basic learning curves, shifts, rotations, rate effects, simultaneous sensitivity/"what-if?" analyses, quantity changes, adjust for lead/lag times with methods for time phasing, and adjustments for design producibility,
- Integrated interface (AACEI) with ship design synthesis tools (ASSET) for real-time cost-design comparison,

[58] Colton and Company, http://www.coltoncompany.com, Arlington, VA.
[59] Defense Acquisition Deskbook Joint Program Office, "Defense Acquisition Deskbook, Version 2.2.87", Wright-Patterson Airforce Base, Dayton, OH, December 15, 1997.

- An automated cost database (ACDB) with the capability to enter, search, and retrieve cost, schedule, technical, and programmatic data, including contractor raw data (mapping and normalizing cost data into standard WBS),
- Cost analysis statistical package (CO$TAT) performs statistical analyses including histograms and scatter plots, linear, log-linear, and non-linear regression, and fit learning curves, cost risk application (RI$K) that performs risk and uncertainty analysis.

The immediate goal of these improvements is to provide ship design managers with robust acquisition cost estimates early in the design process, thus leveraging design trade-offs. However, ACEIT fits within the context of a larger movement in the DoD: the transition from acquisition costs and simple Life Cycle Cost (LCC) analysis to Total Ownership Costs (TOC.)

TOC is the attempt to assess system cost beyond the boundaries of the specific platform (or ship.) In addition to LCC (R&D, acquisition, operations and support and disposal costs), TOC seeks to include appropriate external costs resulting from the development of the ship (i.e. training pipe-lines, repair facility and overhead, combat systems, cost of a sailor, etc.) TOC is incorporated formally in the design process through the methodology of Cost as an Independent Variable (CAIV.)[60] Through the CAIV approach, early phases of the acquisition process (Pre-Milestone I) establish an aggressive, achievable LCC goal based on mission requirements, reasonable delivery schedules, acceptable design baselines and expected budgetary forecasts. At Milestone I, firm cost boundaries are established, as well as goals for LCC reduction (the savings being reflected as TOC.) Design managers seek to optimize system cost, performance and schedule within this context. The key to achieving effective constraints and goals is the inclusion, early in the process, of all relevant life cycle participants. "The Overarching IPT (OIPT) for each ACAT I and ACAT IA (as required) program shall establish a Cost/Performance IPT (CPIPT). The user community shall have representation on the CPIPT. Industry representation, consistent with statute and at the appropriate time, shall also be considered."[61] The inclusion of these participants at the earliest design stages provides cost estimators the ability to assess the impact on cost of critical design decisions such as producibility, combat system design schedules, integrated logistics support (ILS) and other LCC issues. Thus, important impacts can be tested in cost models like ACEIT.

Cost and the optimization of cost goals has dominated the reforms seen in the last decade, particularly as seen DoD directives (CAIV in DoD 5000.) The evolution of cost models along with greater inclusion of life cycle participants is allowing design leverage at the point of greatest effectiveness, early design. However, the question remains…will these enhancements effect only cost, or will the dynamic impacts of cost analysis result in performance degradation and cycle time growth?

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[60] "DoD Directive 5000.2-R, Mandatory Procedures for Major Defense Acquisition Programs and Major Automated Information System Acquisition Programs", Part 3 Section 3.3.3.
[61] Ibid.

1.2 Dynamic Modeling of the Design Process

1.2.1 Need for Modeling

The concerning trends reflected in the DAC study, increasing costs and schedule with lack of system performance assessment, have received substantial focus and improvement efforts. For cost, improved cost models and greater inclusion of life cycle participants have highlighted "stalking horses" that may be tamed to reduce costs. As for performance, greater customer focus within the context of improved system requirement and performance assessment provides better means to trade performance against factors of cost and schedule. Even cycle time may realize significant improvements with the inclusion of IPTs, evolving acquisition strategies, and computer based data management and assessment. However, unlike cost and performance, naval design process time has not received mush effort towards the creation of robust, strategic assessment tools. Naval design managers lack the ability to effectively trade-off schedule with process improvements. This shortcoming is important considering the three primary variables: cost, performance and schedule. The difficulty in managing a successful program results from the fact that "...the vectors of these variables are highly interdependent and non-linear."[62] As noted previously, the improvements to costing and performance naturally impact the schedule through inclusion of new design participants, increasing levels of desired design tasks early in the process or introduction of previously unused or unavailable assessment tools.

Traditional project modeling tools, such as PERT and CPM, do provide a tool for assessing the direct impacts of such changes, but often fail to capture critical feedback and dependencies within the engineering and production process.[63] As a modeling technique, system dynamics can effectively capture such non-linearity and, thus, provide better understanding of the modulations of the variables under consideration. With respect to project management, system dynamics has been proven for numerous specific applications and cases.[64] However, system dynamics has been primarily used for high level or very specific decisions and often lacks sufficient structural detail to apply to a specific process (such naval design.)[65]

A need has developed to provide program managers with a dynamic process tool appropriately adjusted to reflect the realities of naval design.

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[62] ADM Wayne Meyers (USN ret.), interview, Techmatics Inc., Arlington, VA, November 13, 1997.
[63] Rodrigues and Bowers, "System Dynamics in Project Management: a Comparative Analysis with Traditional Methods", System Dynamics Review, Volume 12 Number 2, summer 1996, page 130.
[64] Ibid. page 128.
[65] Ibid. page 133.

1.2.2 What is System Dynamics?

System dynamics is rooted, like its founder Dr. Jay W. Forrester[66], in the engineering traditions of control theory and feedback analysis. Three characteristics distinguish system dynamics from traditional management support tools[67]:

- Its foundation is engineering science, not statistics,
- It relies on data to support, not control model development, and
- It presents a dynamic, not static, environment for decision analysis.

Specifically, system dynamics emphasizes the construction of models that capture the process of a system based on explicit casual relationships of variables within a closed-loop feedback structure. Data is used to calibrate the model, but the verification of a model relies on common sense (agreement of the operation of the real world and the model structure) and formal mathematics (accumulations and flows based in differential calculus.) The resulting model relies on complex, non-linear relationships to dictate behavior, rather than linear, statistically based associations. System dynamics models still incorporate statistics during analysis as a means to test the sensitivity of model assumptions. But this analysis is intended to further validate the model rather than drive model development. Finally, model results are meant to be used as strategic tools to compare policy impacts, not produce explicit results (such as exact cost or a definitive time table.) A validated model, which demonstrates generally accurate behavior (variable fluctuations, dynamic convergence or divergence, and representative process structure) provides a means to assess policy options for "order of magnitude" relationships.

System dynamics is widely accepted as an assessment tool. During the late 1950's, Dr. Forrester, an MIT researcher responsible for the invention of random-access magnetic computer memory, accepted a position with the Sloan School of Management. His interest was the application of control theory to social systems such as business and industrial processes. Since that time, his analytic approach has blossomed into an accepted field of social policy analysis with numerous successes including:

- *Urban Dynamics*, a study of the policy impacts of urban housing developments,
- *Limits to Growth*, a study of earth's ability to sustain mankind under current environmental trends,
- *The National Economic Model*, a study of business cycles in the United States, and
- numerous business and social process models.

These models, as well as previously mentioned models (1.1.1 and 1.1.2), are particularly useful in their ability to show why a seemingly useful organizational policy fails to produce the results expected from policy managers.

For example, Analog Devices Inc (ADI) of Norwood, Massachusetts, a producer of high-end integrated circuits successfully applied a Quality Improvement Program to their production process.[68] The goal of the program was the improvement of product quality (reduction of errors), on-time delivery and reduction of production cycle

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[66] Jay W. Forrester, "The Beginning of System Dynamics", banquet talk at the international meeting of the System Dynamics Society, Stuttgart, Germany, July 13, 1989.
[67] Dr. Louis Alfeld, "The System Dynamics Modeling Methodology", Decision Dynamics Inc, 1994, www.decisiondynamics.com.
[68] Robert Kaplan, "Analog Devices: The Half-Life System", Harvard Business School case study, 1990.

time. The improvement process found great success on the production floor within a very limited time (2 years.) However, when management attempted to apply their program to product development, it not only failed, it began negatively impacting the production cycle. A system dynamics model was generated and showed managers that failure to adjust the improvement program goals relative to the time scales of production versus development had generated the failure. Human intuition (if the improvement was effective in production it should be effective in development) failed to understand the dynamics of how the improvement process disseminated through the organization and how the various sectors of the organization are inter-related. System dynamics is effective at showing these process factors.

1.2.3 Modeling Approach and Structure

The procedure for developing and analyzing a system dynamics model is well stated by Randers.[69] The procedure is applied in four stages:

1. Conceptualization
2. Formulation
3. Testing
4. Implementation

With respect to the naval design model, stage 1 is discussed in Chapters 1-4 and stage 2 in Chapter 5. Stage 3 is presented for a few select cases in Chapter 6 and stage 4 will be considered for future application in Chapter 7.

Specifically, stage 1 involves the consideration of the problem to be studied (as stated in Chapter 1.1.1 page 13), temporal behavior of important variables in the problem (such as presented in Figure 1 Combatant Cycle Time Trends) and hypothesis of casual mechanisms within the studied process. To this end, the naval design model examines factors external to the design process for a single surface combatant program (budgeting, performance changes, design resource availability within the context all naval design projects.) However, these factors are not explicitly modeled, rather assumed as exogenous inputs to the model. Endogenous model elements include physical design task flows, design organization relative to design resources, design decision processes and cost constraints to the design process.

Stage 2 presents a specific model for a surface combatant design program (DDG-51 program.) The model builds on elements of previously developed, system dynamics models. This approach enhances mathematical accuracy of the model as well as validity relative to accepted modeling practices. However, the selected model elements are tailored to the behavior modes expressed in stage 1. In particular, the model reflects the impact of naval design task inter-relationships based on the design spiral (Chapter 4.)

Stage 3 demonstrates the model calibrated to the DDG-51 Program (August 1978 through September 1991.[70]) Given replication of baseline behavior by the model, several "What if" scenarios are proposed:

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[69] Jorgen Randers, "Guidelines for Model Conceptualization", Elements of System Dynamics Method, MIT Press, Cambridge, MA, 1980.
[70] Ship Design Group, Ship Design Project Histories Volume II 1980-1989, Naval Sea Systems Command, May 1986, pages 2-8.

1. Application of 3-D Product Models and Simulation Based Design, and
2. Application of Integrated Product Teams and Concurrent Engineering.

The results of these scenarios provide relative assessment of the improvement processes for consideration against accepted "mental models" of how those processes should effect the process.

Finally, stage 4 discusses the future uses of the model as a tool specific to surface combatant programs (like the DD-21 program) when continuously calibrated and adjusted as process improvement results are available or alternative "what-if"'s are asked. As such, the model is proposed for use as a "management flight simulator" in naval design programs. The model may further be incorporated into the structure of larger models addressing complete life-cycle (design through production through operations and support) and cross-programmatic (budget allocation and project phasing) issues. Finally, the model is considered for its potential role as a piece of a larger "cost-schedule-performance" model.

2 Design Process External Influences

When first analyzing the problem of cycle time growth, it is necessary to understand the external influences that constrain and drive the design process. The externalities generally consist of strategic variables and decisions such as total force structure and capability (order of battle), national defense budget and budgetary allocations, threat capabilities and capability differentials (gap between our force and an enemy.) These externalities play a critical factor in cycle time growth. As such, the only true method to reverse cycle time trends is to understand and control the forces of the externalities. However, changes to the overall acquisition and force structure are not within the scope of this thesis. Rather, the goal is to establish a model representative of internal process forces, such that improvements proposed to the internal structure can be assessed. Therefore, we will examine the external influences to recognize their impact on the design process as exogenous inputs, leaving external analysis and decisions to alternate forums. By understanding the effect of external forces, the internal process can be designed to minimize their impact.

The following influence diagram, Figure 10, shows a number of the important reinforcing and balance loops which ultimately effect the design process. The loops represent those cause and effect mechanisms that act in concert with and as feedback to many of the behaviors apparent in the process of budgeting, setting requirements and managing schedules. The loops are influenced by a combination of observed temporal variations (behavior modes), physical responses (decision policies and mechanisms) and structures required to close feedback processes. In particular, note the mechanisms influencing "Design and Acquisition Rate" (instantaneous design cycle time.) The rate is impacted by resource availability, acceptable risk levels and design complexity. The variables shown aggregate many variables (design and acquisition rate represents the average rate for all current design projects.) The diagram also establishes boundaries (primarily encompassing naval ships) that could easily be expanded or contracted to capture additional trends.

These dynamics represent a series of dynamics specifically noted by naval process experts during interviews held August 24-28, 1997, November 12-14 and 19, 1997 and December 8-11, 1997. The interviews included government design managers and engineers (NAVSEA and Naval Surface Warfare Center Carderock Division), commercial design support and shipbuilders (John J McMullen and Associates, Techmatics Inc, SYNTEK Inc., Newport News Shipbuilding, and Bath Iron Works) and academia (MIT and Sloan School of Management.) A complete listing of personnel interviewed can be found in Chapter 8.2.

The dynamics are examined individually to clarify their inclusion in the totality of external process influences.

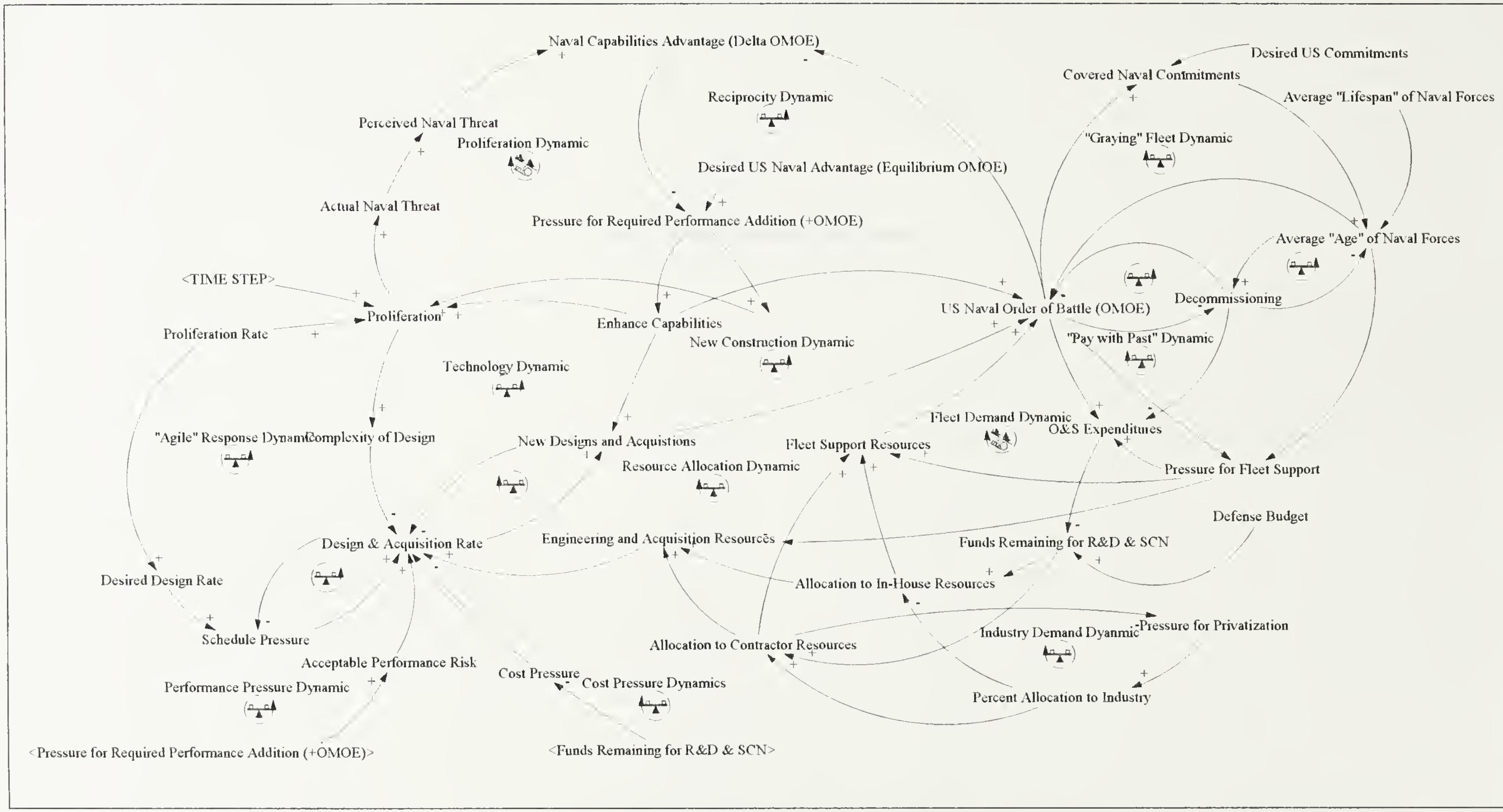

Figure 10 External Design Process Dynamics

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2.1 Reciprocity and Proliferation…the Need for Naval Capabilities Evolution

In his 1996 thesis on the naval ship production process[71], Tim McCue introduced the concept of the "Arms Race Dynamic." This dynamic is shown in Figure 11. There are two dynamic loops at work in this process: the Proliferation Dynamic and the Reciprocity Dynamic. The Proliferation Dynamic is well understood by military strategists and is a source of debate with respect to international control of weapons and capabilities (particularly weapons of mass destruction and "smart weapons".[72]) The Proliferation Dynamic is a "snowballing dynamic" and may be characterized as follows:

1. As new weapons and doctrines are introduced into service by US forces, these capabilities will diffuse (or proliferate) over time such that threat forces possess reciprocal capabilities (either equivalent or negating)
2. As proliferation carries on, US intelligence methods will characterize the threat based on actual and, consequentially, perceived capability of the threat force
3. The perceived threat will be weighed against US capabilities resulting in a US advantage (or deficiency)
4. As proliferation continues, the US advantage will decline and pressures to enhance US capabilities will begin to increase
5. As pressures to enhance capabilities increase, the US forces will improve
6. Force improvements will be noted by the threat force that will in turn seek to gain the same enhanced capability or a negating capability…and so on.

The Proliferation Dynamic has many other details not noted here (such as cost of new capabilities, technological complexity and political landscape) which have significant impact on the rate of proliferation. However, time has shown that proliferation rate may be moderated, but as long as inequalities exist diffusion will occur.

[71] Timothy P McCue, "The Dynamics of Naval Shipbuilding-a Systems Approach", Department of Ocean Engineering Thesis, Massachusetts Institute of Technology, June 1997.
[72] William S. Cohen, Report of the Quadrennial Defense Review, United State Department of Defense, May 1997.

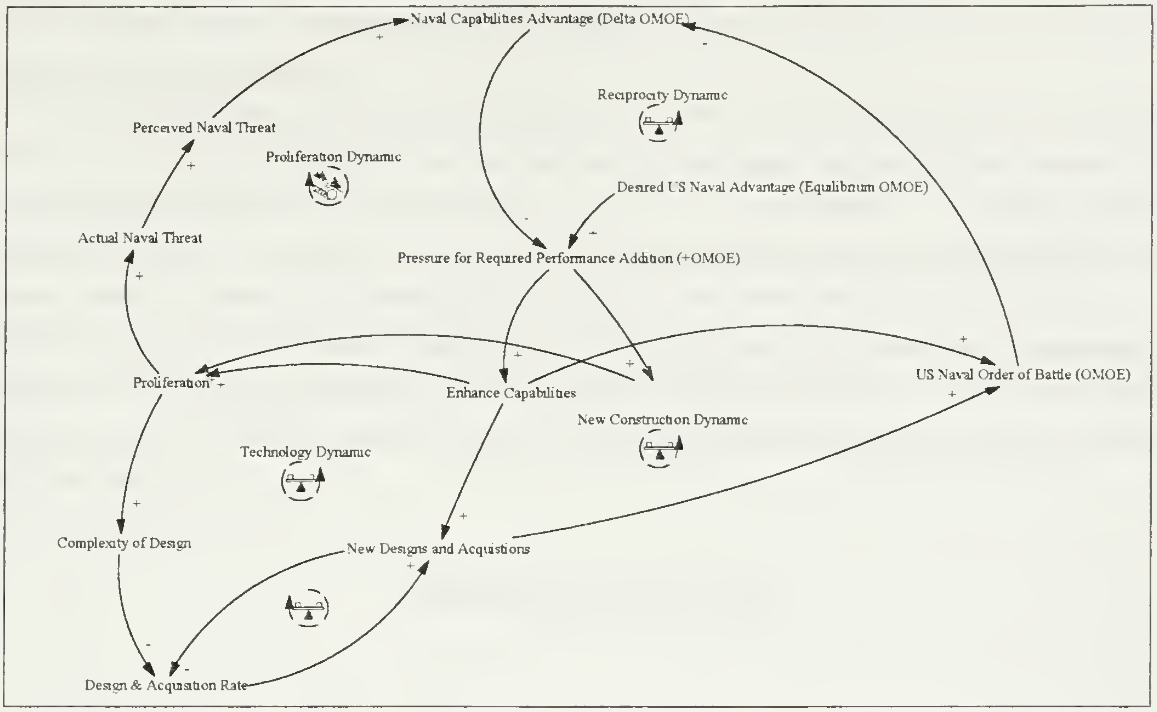

Figure 11 Arms Race Dynamic

In order to balance the threat of Proliferation, US forces must follow with Reciprocity. The Reciprocity Dynamic is characterized as follows:

1. US forces start at a given force level (US Naval Order of Battle)
2. The US force has an inherent capability advantage (or deficit) when compared to potential threat levels
3. Pressures to increase US capability (typically political) increase as the US advantage is decreased
4. The source of new military advantages may originate from new capabilities (new ships, weapons, etc.) or changes to enhance doctrine to employ current forces
5. Capabilities increase the US advantage until pressure to improve is nullified.

As with Proliferation, Reciprocity can be further described by additional variables such as current political climate, defense costs and the state of the US economy, or perceived level of international stability. However, as long as the US continues to choose a role as a leader in world affairs, military strength (advantage) will likely be the doctrine of choice.

Two detailed expansions of the Arms Race Dynamic are also demonstrated. First, the new construction dynamic demonstrates that one method of increasing capability is to develop new weapon and ship systems The construction of new designs (increased with increasing design rates, measured as new designs completed over time) results in the increased order of battle…completing the reciprocity balancing force. A second dynamic expansion is the impact of technology from proliferation. As proliferation of advanced defense technologies occurs, the complexity of new designs required to counter those technologies increase. As complexity is increased, the design rate slows (more time is required to gain equivalent leaps in performance advantage), new constructions slows and

the order of battle decreases…ultimately the ability to maintain capability advantage will be lost to the balancing force of technological complexity.

The "Arms Race Dynamic" lies at the heart of the Naval Design Process as the primary influence effecting the need for new designs, the need to support operating forces, the increasing complexity of newer designs and the acceptable levels of risk relative to cost, performance and cycle time. Consider Figure 12. Correlated against the trends shown in Figure 1 and Table 8, US warships have been dedicating larger fractions of procurement costs to combat systems in response to ever growing threats, while the combat systems themselves are achieving exponentially decaying improvements in capability, and the net development cycle is slowing to accommodate assessment of the threat and development of systems capable of countering those threats. As long as new threats are generated and the US chooses to counter those threats, the cycle will continue to generate the need for a non-zero design and acquisition rate.

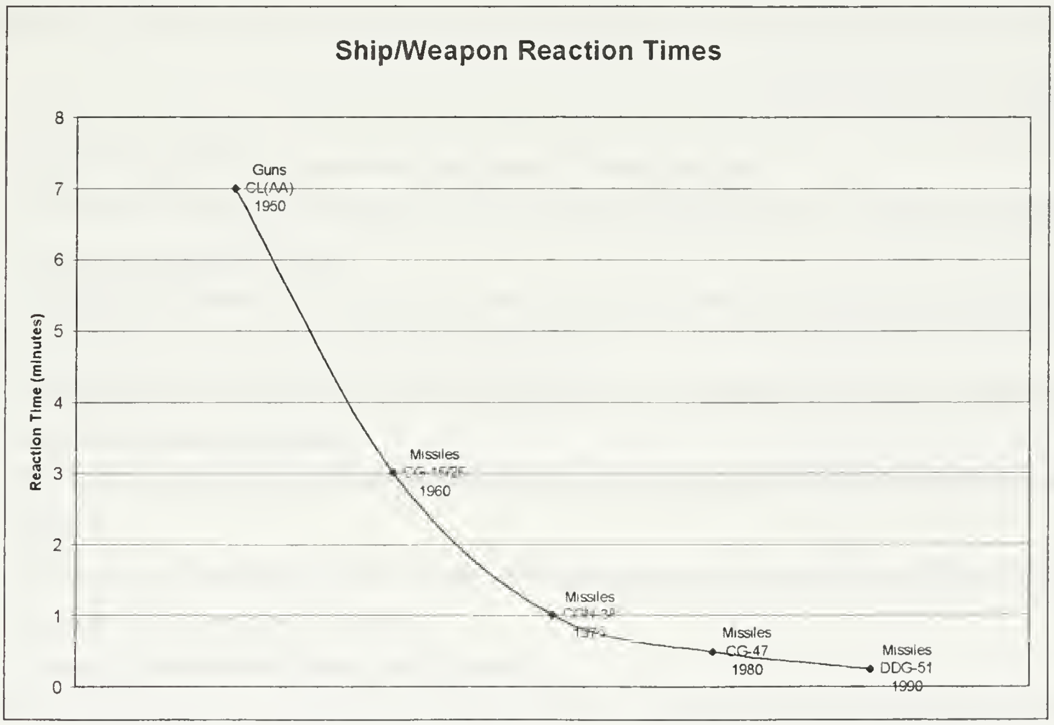

Figure 12 Naval Surface Combatant AAW Reaction Time Trends[73]

2.2 "Order of Battle" Dynamics…Maintaining Force Levels

This second dynamic both drives the need for new designs and counters the ability to produce new designs. Shown in Figure 13, the "Order of Battle" dynamic demonstrates the mechanisms by which even a static threat ultimately requires creation of new designs. First, consider the "Graying" Fleet Dynamic. For a static capability level, time eventually degrades the capability. For Example:

[73] Prof. Charles Calvano, Total Ship Systems Engineering, http://web.npgs.navy.mil.

1. The current US aircraft carrier capability is known (Figure 14).
2. The desire for the US to engage specific commitments (Persian Gulf, Adriatic or South China Sea) results in carriers being assigned to the regions.
3. As commitments increase for the fixed number of carriers, the average aging process for those committed carriers increases.
4. As carriers age, the useful life is expended until decommissioning. This increases the average age of the total fleet but at the cost of reducing the overall order of battle.
5. Finally, as the age of ships increases and fewer are available due to decommissioning or increased maintenance time for older vessels, the order of battle decreases…

These balancing forces (meeting commitments ultimately means not meeting commitments) are reversed by the counter-balance of the reciprocity dynamic. This is one of the factors currently driving the CVX program to replace aging carriers (Figure 14.)

An additional dynamic proceeds from the "Graying" Fleet dynamic…Fleet Demand Dynamic. By this dynamic:

1. Increased fleet age (as a result of time and increasing commitments) generates pressure from operating forces to devote funds to maintenance and support of operating ships
2. The pressure increases as the total force level increases and limited funds are allocated across a larger inventory of operating vessels
3. The pressure translates as an increased demand on engineering resources (commercial and naval) to be dedicated to fleet support vice development activities,
4. The pressure forces increased operation and support (O&S) expenditures within the fixed constraint of total available defense budget,
5. The increase of fleet support resources and O&S expenditures reduces available funding for development projects,
6. The increase of fleet support resources and O&S expenditures improves the Order of Battle which increases naval commitments covered,
7. Ultimately increasing the average age of vessels…

The result is reinforcing behavior…aging ships demand resources to maintain force levels which demand more resources and so on. This behavior fueled much of the deficit spending required to supported the defense build-up of the 1980's.

A third behavior has been especially apparent in the last few years, a trend to pay for newer capabilities with the decommissioning of older vessels…"Pay with Past" dynamic. Consider the following trends:

1. For a given force level (order of battle) decommissionings may be considered to reduce O&S expenditures,
2. As more ships are decommissioned, O&S expenditures decrease which increases funds available for procurement (R&D and SCN),

3. Allocations of procurement funds to industry and government resources result in a pool of Engineering and Acquisition Resources,
4. As this pool increases the design rate (new designs produced over time) increases and new designs and acquisitions result,
5. Ultimately increasing the order of battle in the form of new ships and capabilities.

This behavior is balancing…decreasing order of battle with decommissioning will increase order of battle with new construction. During the down-sizing of the 1990's, many new construction programs and upgrades to operating units were funded with the decommissioning of older vessels. However, the majority of the recovered funds were lost to a shrinking defense budget and increases in O&S funds required for support of US commitments (Somalia, Haiti, Bosnia, Persian Gulf, etc.)

A final behavior of note is the Industrial Demand Dynamic. Proposed by Dr Harvey Sepulski[74] (Massachusetts Institute of Technology), this dynamic has received significant focus from the defense industry in recent years:

1. If allocations for contracted resources decreases (due to decreasing defense budget funds), there is increased pressure from industry (on Congress and on government acquisition authorities) to privatize government operations
2. As pressure increases, greater portions of funds are given to industry,
3. The increased allocation to industry decreases pressure for privatization…

The result is a balancing force within the defense industry with respect to available defense funds. Note that increasing privatization must be coupled with decreased in-house resources for a fixed budget.

The dynamics of these Order of Battle factors impacts the design rate through fund allocations (giving and taking from development programs) and as factors requiring the introduction of new forces to replace older ships. Many of these dynamics are currently being examined by industry as potential areas for privatization of fleet support expenditures.[75]

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[74] Presentation to Ocean Systems Special Project course at Massachusetts Institute of Technology, Spring 1997.
[75] Prof. Jim Hines, Applications of System Dynamics course project supporting the Boeing Corporation, Sloan School of Management, Cambridge, MA, Spring 1998.

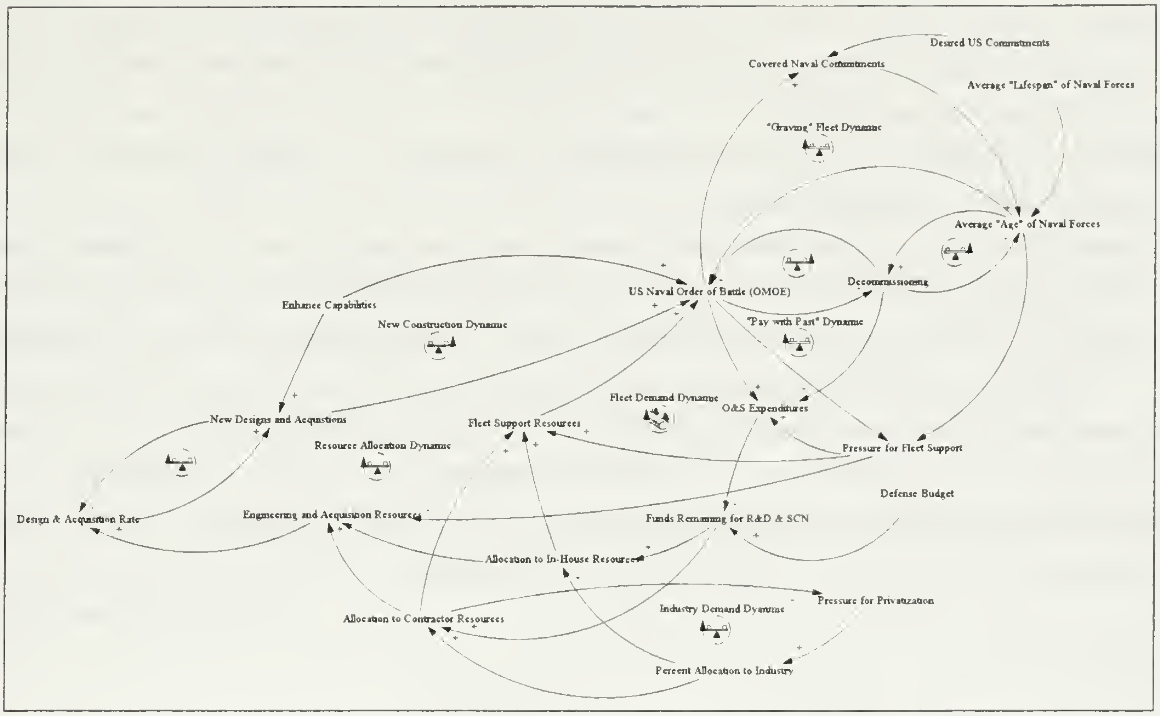

Figure 13 "Order of Battle" Dynamics

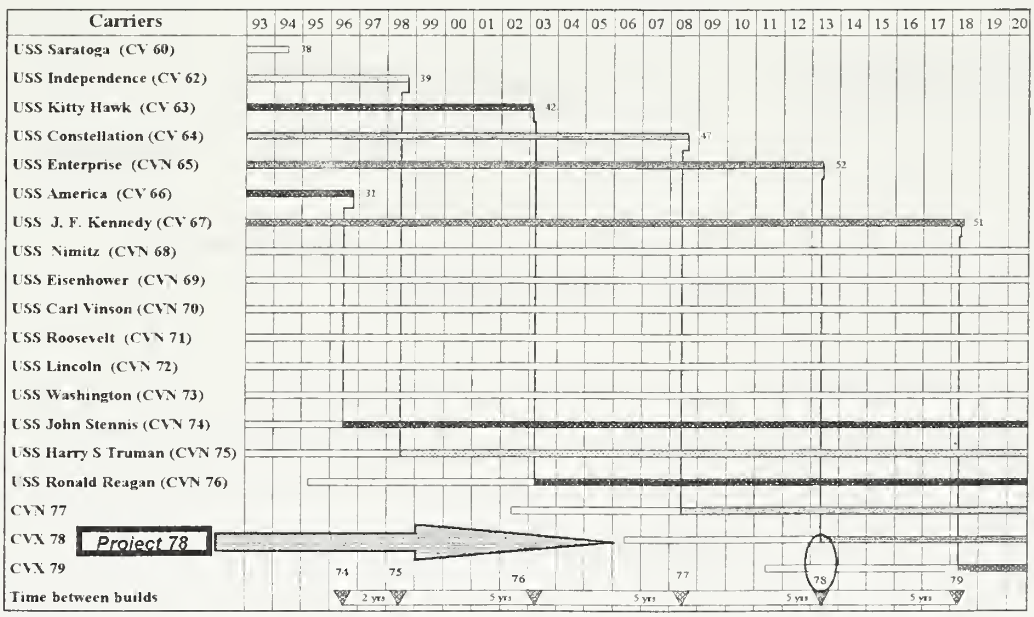

Figure 14 Timeline for US Aircraft Carrier Development and Decommissioning

2.3 Design & Acquisition Rate Influences

The cycles of the Arms Race and Order of Battle are shown to demonstrate their influence over the topic of primary concern: Design Rate. In particular, it is important is understand how these dynamics control design rate

(and, thus, design cycle time) through the functional input of performance and cost. Figure 15 shows an expanded view of these inputs. It has already been shown implicitly that design rate is impacted by changes taking place in cost and performance (Chapters 1.1.2 and 1.1.3) as well as by the dynamics of performance requirements (Chapter 2.1) and cost constraints (Chapter 2.2.) Design rate is also explicitly impacted by cost and performance constraints. Consider the case of the DDG-51 program. During the preliminary and contract design process, design managers applied an approach of a "closed loop feedback control process of establishing budgets, reviewing the design for conformance to the budgets, and making decisions to change the design (within performance constraints) where design features exceeded the established budget."[76] Figure 16 demonstrates this form of "dynamic cost control" with an exponential increase in cost from an initial baseline through the end of the Feasibility Design Phase followed by a very rapid oscillation beginning in May 1983 to stabilize the cost ($700M follow-ship acquisition cost in FY83$.) Coincidentally, May 1983 represented the official start of the Contract Design Phase…a period during which cost becomes very apparent and engineering manpower rapidly ramps-upward to facilitate increasing design tasks[77]. The result of this process was a lengthening of the design schedule by several months to accommodate the additional analysis and review.[78]

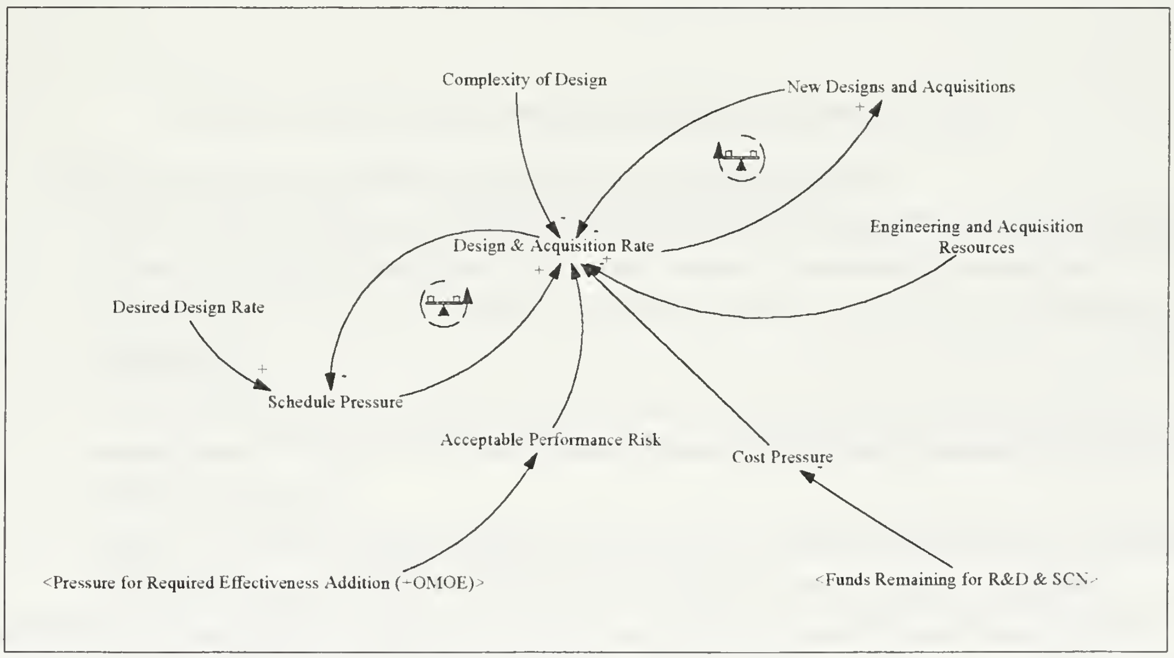

Figure 15 Design Rate Dynamic Inputs

[76] Hope and Stortz, "Warships and Cost Constraints", Naval Engineers Journal, March 1986, page 43.
[77] Ship Design Group, Ship Design Project Histories Volume II 1980-1989, Naval Sea Systems Command, May 1986, pages 2-8.
[78] Hope and Stortz, "Warships and Cost Constraints", Naval Engineers Journal, March 1986, page 46.

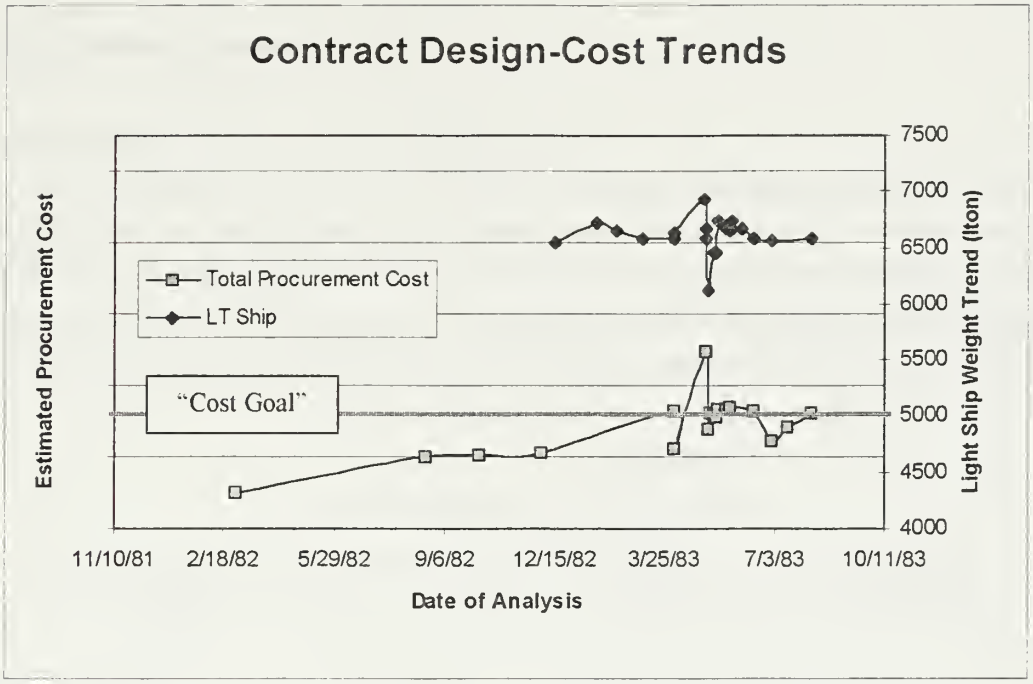

Figure 16 DDG-51 Contract Design Procurement Cost Estimate Trend[79]

These inputs and cycle time dynamics are explained by the following influences:

1. Increases in design complexity (performance required) lengthen the design process (slow the design rate)
2. Decreases in design funds and engineering resources lengthen the design process as acquisition authorities become risk adverse (hesitant to commit funds) and basic resources become diluted among design projects
3. As perceived threats from proliferation and decreasing US advantage become apparent, pressures to increase design rate (shorten cycle time) come from reduced schedules and willingness to accept greater design-performance risk
4. Finally, as the volume of designs in progress increases, the rate naturally adjusts (balancing) as schedules for immature designs are relaxed to focus resources on designs in the later stages of completion.

These influences represent the input variables that must be considered for inclusion in a design process model. However, these variables are external to a specific design project. Although a design manager must consider issues such as increasing performance requirements or reduced funding from the defense budget, he has little control over budget allocations to other programs or the cancellation of a technology pipeline by a sister service in the DoD. As such, these variables are included as exogenous inputs to the model. The model provides a means to change the assumptions of the inputs, thus allowing the gaming of potential scenarios driven by those influences.

[79] Vernon E. Stortz, "DDG-51 Design-Cost Trend Log", unpublished, Naval Surface Warfare Center Carderock Division, Bethesda, MD, August 1984.

3 Design Process Dynamics

3.1 Systems Engineering and Naval Ship Design

The naval ship design process is the process of establishing a military need, defining this need in terms of military requirements and constraints, performing a set of design tasks to develop a solution, validating the solution versus the requirements, and translating the solution into a form usable for production and ship support. Figure 17 demonstrates this concept and it's iterative elements. These steps are repeated at each stage of the design process, from concept to production design, with the detail of the tasks increasing concurrently with the maturity of the design.

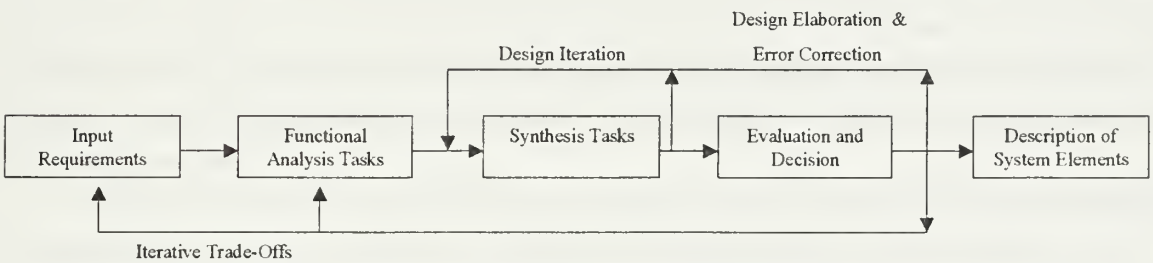

Figure 17 Systems Engineering Process[80]

The dominant accumulations and flows in this generic process are as follows:

1. Input requirements generation (such as threat analysis and Mission Need Statement (MNS) generation) with tasks for analysis of mission needs
2. Functional analysis tasks (such as Industrial Base Assessment and Analysis of Alternatives) that establish reasonable system options
3. Synthesis tasks (such as hullform design or combat systems integration) that define and optimize the system
4. Evaluation and decision (such as ship vulnerability modeling or milestone approvals) with tasks to examine and approve or disapprove completed design tasks, and
5. Description of System Elements (such as Contract Specifications or Construction Drawings) to translate system requirements into component and production specifications

Several important feedback flows are apparent in the process. Iterations may result from physical design balance, design errors, risk mitigation, scope change, and modification of input requirements. Physical convergence is centered on design synthesis.

Synthesis in naval ship design is modeled in the design spiral. The dynamics of spiral concurrence and information transfer are a unique property of naval ship design. A more detailed discussion is presented in Chapter 4.

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[80] Kockler, Withers, Poodiack and Gierman, Systems Engineering Management Guide, Defense Systems Management College, January 1990, page 1-3 and 5-2.

An important source of feedback is error discovery and correction. Errors themselves may be generated at any stage of the process. Early in the process, errors occur when objectives and requirements are erroneously or imperfectly specified. The mechanisms described in Chapter 1.1.2 are designed to mitigate the probability of errors in these stages. During later stages, errors may be caused by communication disruptions (design hand-offs), misinterpretation of specifications, inaccuracies or singularities in design algorithms (computational inaccuracies, design modeling assumptions or discontinuities in design variables), and human factors.[81]

Error detection and management typically occurs during specific Quality Assurance (QA) stages. QA is defined as "a set of activities performed in conjunction with a (project) to guarantee the product meets the specified standards…these activities reduce doubts and risks about the performance of the product in the target environment."[82] As errors are detected, the deficient tasks are returned to an appropriate stage for correction. As demonstrated in Figure 17, error correction typically returns to synthesis. For this reason, it is possible that the correction stage may not be the source of the error, thus providing the potential for future error generation. Note that this is a reason for the emergence of Total Quality Leadership (TQL) within the Navy as a method to analyze errors and their causes.

A final source of iteration is the modification of requirements and functional analysis products resulting from evaluated designs. These modifications can include design changes (failure of the current design to meet requirements) or changing requirements themselves (necessitated by cost or performance trade-offs.) Additionally, as the project proceeds through time, the requirements themselves change in response to changing external needs. The result is scope growth. Such growth has a negative dynamic impact: reinforcing work to be done and often dominating the balancing effects of iteration Consider a study of scope change impacts conducted by the Construction Industry Institute.[83] The study examined the change in productivity resulting from increasing fractions of change. The study compiled data for 104 projects from 35 different companies. The results showed that engineering productivity (measured as a ratio of earned work-hours to expended work-hours) decreased linearly at a rate of 5% productivity for 10% increase in design changes. The effect translated into similar productivity decreases for construction.

3.2 Acquisition Process…Points of View

To facilitate the management of the above systems engineering approach, the Department of Defense has formalized the stages and processes. The formal process is referred to as the acquisition process. Figure 18 shows the major phases and milestones of the acquisition process. The acquisition process includes many steps that extend both before and following systems engineering. For instance, pre-Milestone 0 includes not only requirement definition (Determination of Mission Need) but also the examination of available technologies (Science and Technology) that would be required to support Functional Analysis (Concept Exploration.) The examination of

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[81] Abdel-Hamid & Madnick, Software Project Dynamics: an Integrated Approach, Prentice Hall, New Jersey, page 95-96.
[82] Ibid., page 101.
[83] Construction Industry Institute, "Quantitative Effects of Project Change", CII Source Document, March 1990.

technologies may itself be a systems engineering exercise as managed research solutions must be constantly assessed for the range of applications to which those technologies are being developed. The acquisition process also extends beyond production level engineering at Phase II (Engineering & Manufacturing Development.) Specifically, the acquisition process manages the complete production (Phase III) and support (Operational Support and Demilitarization & Disposal) for the fielded system. As such, the acquisition process encompasses not only system development, but the entire life cycle of the system.

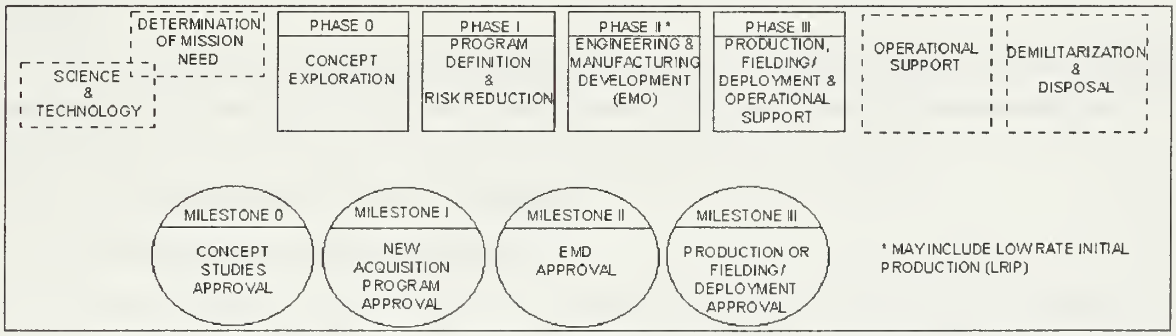

Figure 18 Acquisition Milestones and Phases[84]

Perhaps the largest difficulty in understanding the naval ship design process (or any defense design process) is the large field of views that process observers may take. Consider Figure 19 below. This diagram shows the range of management considerations (shown as timelines) contained within the DD-21 acquisition process. Within this program, participants may take widely differing process views based on their own requirements to focus or optimize process efforts relative to a particular trade-off. For instance, the primary engineering focus is the sequence of design reviews (ASR through FCA) necessary to define conceptual baselines, system definition and design producibility. The engineering view seeks to provide the best physical system (performance) as a response to the given requirements. Alternatively, budgetary and fiscal managers are focused on milestone relationships, since the satisfaction of specific milestones translate directly into funding increases required to support continuing levels of design effort. Additionally, budgetary managers optimize the use of funds against budgetary and fiscal risk. Industry and acquisition managers must concentrate on the various contracting phases (in addition to the other process phases) in order to maximize allocation of intermediate program funds (such as support contracts) while remaining poised to compete for the final contract award. Additionally, industry managers seek to optimize producibility relative to their own production processes. Through optimization of cost and schedule, industry seeks to gain a competitive advantage for contract award.

Each of these points of view are seeking to develop a systems level optimization of the final design. However, the optimization is relative to the area of concern to the particular component managers. This is not to say that component managers ignore total system optimization. They are quite aware of the potential impacts resulting from changes to a particular system element. They are especially sensitive to the impacts of changing inputs

[84] Defense Acquisition Deskbook Joint Program Office, "Defense Acquisition Deskbook, Version 2.2.87", Wright-Patterson Airforce Base, Dayton, OH, December 15, 1997.

resulting from system interdependencies. Ever changing requirements of the military and resulting changes in optimization priorities dictate that no one element dominates through the entire design process. As such, component managers must constantly strive to champion their system element to achieve necessary consideration in the final design. The dynamic impacts of these changes have already been demonstrated (see discussions of Table 2 and Figure 16). These competing relationships and task interdependencies are examined in detail in Chapter 4. The immediate results of compartmentalized and competing demands are obvious: each component manager pushes forward with necessary tasking despite changing priorities and no one component view delivers total system optimization.

In this environment of competing system interests, it is the task of the program manager to assess the needs of the developing system, determine the range of available resources, and assign priorities to optimization goals. Within this context, the program manager works to the following principles and objectives:[85]

- Ensure effective design and price competition.
- Improve system readiness and sustainability
- Increase program stability through effective long-range planning, use of evolutionary alternatives, realistic budgeting and funding of programs for the total life cycle, and planning to achieve economical production rates
- Delegate authority to the lowest levels of the service that can provide a comprehensive review of the program.
- Achieve a cost-effective balance between acquisition costs, ownership costs, and system effectiveness in terms of the missions to be performed

Given this range of responsibilities and management decisions, the program managers tasking in the design process naturally extends to all facets of the project. This fact is explored more fully in Chapter 4.4.

[85] Kockler, Withers, Poodiack and Gierman, Systems Engineering Management Guide, Defense Systems Management College, January 1990, page 2-1.

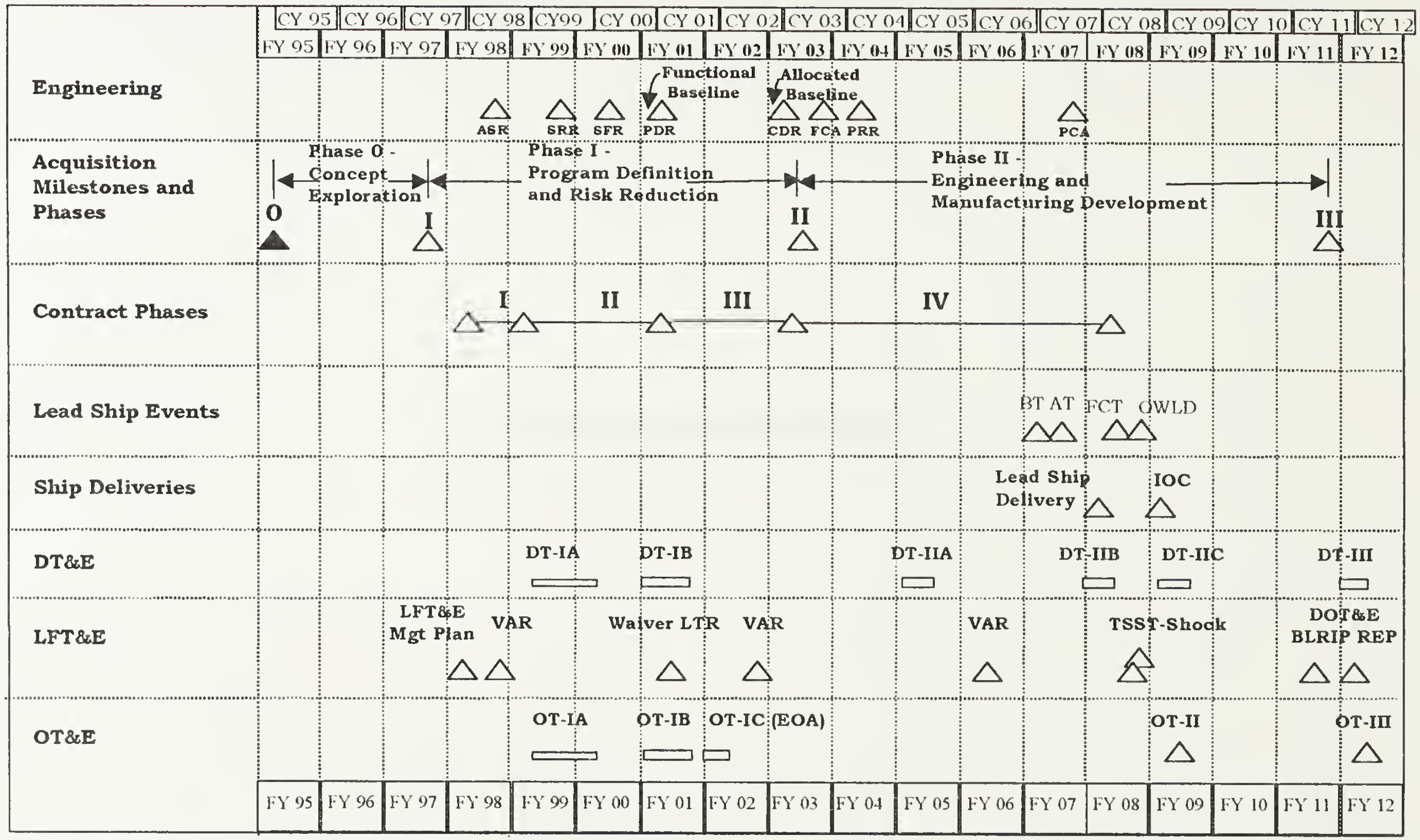

Figure 19 DD21 Lead Ship/System Schedule (Nov 1997)[86]

[86] Michael Gutermuth, Request for Proposal N00024-98-R-2300, DD-21 Program, Washington DC, November 12 1997.

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3.3 Operational Process View

3.3.1 Design Phases

Increasingly, naval ship design is becoming a subset of total ship systems engineering (TSSE). Ship concept exploration and combat system development must begin well in advance of the actual ship design process. As such, the superset of system design spaces will encompass many layers of system optimization and process views. The global externalities described in chapter 2 represent a strategic view of the design process. The system design and acquisition processes described in sections 3.1 and 3.2 represent macro views of the design process. The remaining views are operational views. The operational views provide the exacting structure that is necessary to capture the dynamics of design process change relative to process improvements. Specifically, the operational views are represented by the notions of **Design Phases** and the **Design Spiral**. The design spiral is examined in detail in chapter 4. This section examines the four phases of naval ship design: Concept Design, Preliminary Design, Contract Design and Detail Design.

Concept Design is the phase during which the solution space is examined to identify potential cost-effective solutions to the stated requirements. In the acquisition process, this stage is represented by all activities prior to Milestone I. The requirements are presented by the ongoing **Requirements Definition** subphase during which warfighters recognize an operational need and translate that need into requirements for engineering and acquisition. The overall ship system is emphasized with specification of components limited to a few significant system drivers, such as weapons or propulsion plants. The products of the Concept Design are a set of defined requirements and a design space of achievable solutions to requirements.

Note that the iterative properties of the macro view of systems engineering are present both externally and internally. Externally, the concept design phase represents the first stages (requirements and functional analysis) of systems engineering. Internally, concept design contains explicit elements of all system engineering steps…requirements, synthesis, approval and description of system elements for the next phase. These internal and external characteristics are common to all design phases.

Preliminary Design is that phase during which one or a few desired concepts are refined by analysis and integration of specified components to confirm acceptable system capabilities. In the acquisition process, preliminary design is represented by Phase II (or more often Phase IIA.) The purpose of preliminary design is to focus on overall system effectiveness and assurance that specified systems can be technically and economically supported by the ship design. In particular, engineers and managers concentrate on high risk elements of the design. Such high risk elements may include: industrial base support, combat systems integration, hullform performance characteristics, life cycle cost, or optimization of marine systems efficiency. As a result of in depth analysis of specific systems, the products of preliminary design contain increasing degrees of component specification, but still focus primarily on system level definitions.

Contract Design is the specification of design attributes necessary to reduce risk for the Navy during the award and construction of the selected design. The contract design process is still functionally oriented. However,

increasing numbers of components are specified in detail. Specifically, design attributes are specified by contract specifications to constrain design performance and reduce risk. These constraints may in turn constrain costs, possibly to the detriment of the design process. Like preliminary design, contract design is part of phase II of the acquisition process (or phase IIB).

It is important to note that the traditional design responsibility up to and including contract design has resided with the Navy. As discussed in Chapter 1.1.1, NAVSEA would conduct the bulk of engineering analysis with contractors providing support services, but providing little influence over the direction of the design. However, this trend is changing. Recall the transition points shown in Figure 5. Under the old (DDG-51 and prior) approaches to surface combatant design, the end of contract design represented the transition point of the design from the government to the shipbuilder. Under this approach, the shipbuilder received very specific contract and military specifications directing the materials, components, and even production methods for the design. As shown previously, the result of this inflexibility was delays due to late GFI/GFE/GFM, schedule and cost growth in excess of marginal scope changes, and increasing ship production costs. To counter these effects, current programs (DD-21) are pursuing earlier transition of design responsibility. By specifying performance requirements, shipbuilders are free to pursue design alternatives optimized to their production capabilities. Although the contractors will assume early design responsibility, there must still be a detailed contract specification prior to shipbuilding contract award. This contract specification is necessary to define the product for which ship construction funds (SCN) are allocated as well as commit the shipbuilder to legally binding design performance (i.e. a performance specification will not hold the weight of a contract specification in a court of law.)

Detail Design is the phase during which system descriptions are translated into the instructions required to support construction, operation and support of a finished ship. Within Detailed Design are four sub-phases required to support contractual and production requirements. During **Functional Design**, the shipbuilder specifies ship system components and verifies that the selected systems will satisfy performance requirements. Functional Design provides the linkage between desired system configuration and specified performance predicted by contract design and realized system performance available from a producible design. Functional Design is sometimes associated with contract design by the notion of **Contract Definitization**. This is potentially significant when multiple lead ship contractors are bidding for a project. During such instances, functional design represents a further demonstration of design quality and cost for differentiation of contract bids. However, experience has shown that lead ship design awards typically proceed in advance of contract design end. As such, functional design becomes the initiation of detailed design concurrent with completion of contract design. **Transitional Design** takes the ship system description and incorporates it into a process-based description. Long lead items (propulsion engines, propellers, combat system components, etc) and material requirements lists (MRL's) are incorporated into the shipbuilder logistics system. **Zonal Design** develops components into drawings consistent with the work breakdown structure required for ship construction. After this subphase, the Navy will own and, within contractual limits, distribute the design to all ship builders who have successfully bid for a construction contract. For this reason, these first three sub-phases of detailed design (Functional, Transitional and Zonal Design) are often referred to as **Lead Ship Design**. For a lead ship design effort, the products are intended to support all ship builders and

component vendors participating in the ship construction program. However, the actual process will often result in detailed design attributes that support the construction of the ship in the Lead Ship Yard. As such, participating yards will necessarily modify the Lead Ship Design to be compatible with their production processes. The result is the very notable difference between ships of a common class built in competing ship yards. The final stage of design, **Production Design** or **Manufacturing Engineering**, begins as soon as engineering and production resources, as well as zonal design products, permit initiation. Production Design extracts the final drawings (lofting) and manufacturing instructions required to produce the ship. This phase also provides the interface with the construction site to resolve design conflicts encountered during construction.

3.3.2 Scope Change Implementation and Detailed Design

Detailed Design is influenced by dynamics encountered due to "Internal Change" (producibility accommodations, error and interference) and "External Change" (engineering change proposals and GFI/VFI changes).[87] Internal Change represents those factors over which the design organization has some degree of control. Internal changes include Engineering Assistance Requests (EARs) or producibility enhancements. The dynamics of internal changes require assessment of the improvement versus detrimental impacts. For instance, error rates can be reduced with increased QA. However, increased QA naturally delays the schedule and commits valuable resources away from tasking. Thus, a trade-off must be determined internal to the project. External Changes are those factors over which the organization has little control. External changes are either Navy Engineering Change Proposals (ECPs) or vendor changes. For instance, as requirements change, the design must change (despite the negative system impacts of change) otherwise the design fails to meet the perceived need.

All changes are analyzed for schedule, material and production impact. The level of analysis varies depending on the complexity of the change. A simple interference identified by an EAR will be analyzed by the production design representative on the waterfront and processed in accordance with standard procedures. A complex ECP is analyzed by system and functional engineering, design, material engineering and planning specialists. If the proposed change is considered necessary, an action plan is developed which integrates the change into design and construction process.

Design changes originating during the construction process are provided to manufacturing as interim products known as "Revision Notices" (RNs). Through a "lock-step" process, fabrication and installation drawings extracted from the CAD models are continually maintained to reflect the current design baseline via RNs. It is essential that configuration control of the models and drawings be maintained while new design changes are introduced. Revised drawings are reproduced at regular intervals to support the next follow on hull that take into account the multiple design changes created during the construction of the previous hull. During these maintenance cycles, all outstanding change paper is accounted for and a "clean drawing" is produced. Similar to the lock-step process, parts lists are continually updated as changes are identified. External Change and Internal Change are specific representations of scope growth of a project.

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[87] C. R. Lloyd, "Design Process for the AEGIS Destroyer Program", Presentation, Bath Iron Works D87 Class Design Office, November 18, 1997, page 6.

4 *Design Spiral and Task Dynamics*

4.1 "The Design Spiral"

The design of a ship is not the act of designing specific equipment…rather; it is the integration of systems and equipment to optimize cost and effectiveness.[88] Such activity is inherently multi-disciplinary ("no single person can be expert in all these areas"[89]) and highly iterative. However, this is not to say that the process is without recognizable structure and organization. To the contrary, the naval ship design process must follow very specific steps and satisfy fundamental physical laws in order to achieve a balanced design. These balanced properties range from the most basic (hydrostatic balance, resistance-to-powering balance, structural stress-to-integrity balance, etc) to those demanded for increased effectiveness and decreased cost (passive-vs. active-defense trade-offs and design optimization vs. producible design.)

The most widely accepted methodology used to balance design requirements to ship components is the design spiral. The design spiral describes the process that compartmentalizes the design disciplines and regiments the engineering steps necessary for a balanced design. Figure 20, shows a typical example of such a spiral. (Note that the concept of the design spiral is attributed to Professor J.H. Evans of MIT and was first introduced in the Naval Engineers Journal, November 1959.)

Fundamentally, the spiral is a ship-system algorithm that combines physical relationships with trade-off options. The spiral is characterized by a sequence of specific tasks that incorporate initial design requirements, synthesize these requirements into a set of design characteristics, assess the design characteristics against the requirements and against one another, and iterate as necessary to achieve convergence of the values. The design spiral relies on three important features to enable analysis and convergence. First, the design space from which all potential design characteristics may be chosen is not infinite. Rather, the design translate into a specific design space (known as design lanes.) These design lanes enable engineers to assume a set of initial ship characteristics and, thus, proceed with the design analysis. Secondly, the spiral generates specific design characteristics and modifies the values as necessary to meet requirements. As such, the design assumptions at the beginning of a spiral differs somewhat from those at the end of an iteration. The spiral process incorporates the new design values into each successive iteration until the values converge to a balanced design. Design balance indicates the defined ship characteristics are physically stable while satisfying design requirements. It is important to note that a balanced design may not necessarily represent the optimal design.[90] Finally, as iterations proceed and convergence is achieved, the process of synthesis and analysis seeks greater and greater levels of detail. For instance, initial structural analysis incorporates simple beam theory, ship section modulus and accepted design practices. Later

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[88] Gale and Scott, "Early Stage Ship Design Seminar", The Society of Naval Architects and Marine Engineers, October 1995.
[89] Tibbitts and Keane, "Making Design Everybody's Job", Naval Engineers Journal, May 1995, page286.
[90] Allan Andrew, "Multi-Attribute Decision Making Analysis with Evolutionary Programming Applied to Large Scale Vehicle II", Thesis for Ocean Engineering, Massachusetts Institute of Technology, Cambridge, MA, May 1998.

iterations incorporate greater design detail such as finite element analysis for both static and dynamic loads. Finally, the design incorporates structural arrangement details necessary for construction. Each increase in detail requires comparison of design characteristics for convergence. The result is a convergent, producible design and greater confidence with respect to design requirement risk.

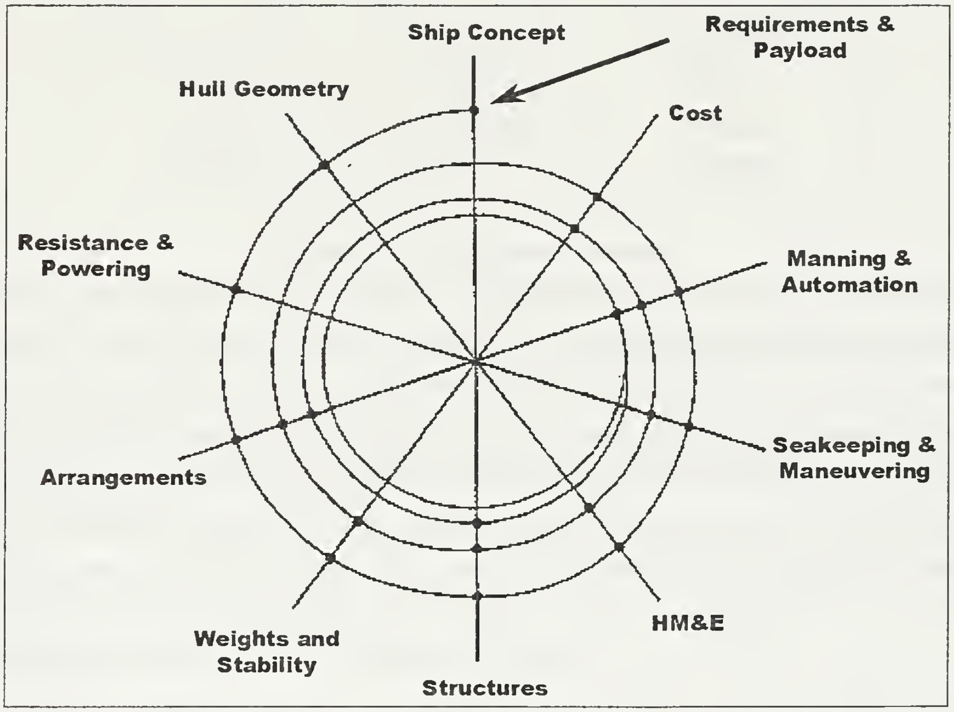

Figure 20 Generic Ship Design Spiral

There is no one spiral that is correct for all ship designs. A proposed spiral must incorporate design and analysis elements necessary to satisfy requirements. In particular, the spiral task elements may vary by mission requirements, level of risk mitigation required or level of sub-system and total system maturity. For those general design disciplines that are chosen for a given spiral, sub-spirals may be necessary within a design node in order to generate and analyze specific design characteristics. For example, it is necessary to balance auxiliary system capacity to electrical power generation to payload support requirements within the marine engineering discipline. The consequence of layers of design and analysis is a set of nested iterations of design within the overall design structure. Figure 21 shows an example of this concept. Additionally, the view of the spiral may change to accommodate varying process interpretations: viewed as either moving from the outer rings inward or from the center outward. If outer to inward, the view is one of considering the initial development of numerous conceptual designs with each narrowing ring focusing the effort to fewer and fewer design options and culminating in a single final design. Alternately, the view of increasing arc lengths from center to outward represents the increasing detail

required of each iteration to validate the final design.[91] Whatever the view or structure, the spiral provides a common baseline to begin discussion of design process and disciplines necessary to develop and evaluate the design.

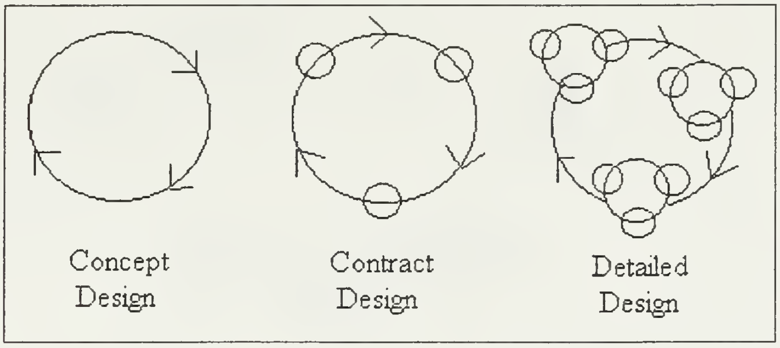

Figure 21 Nested Design Iterations

These views of the design process are consistent with the basic structure for project models utilized in system dynamics. Namely, the iterative nature reflects a necessity to take a set of initial (or baseline) tasks to be done, perform those tasks to a level of productivity, and rework the tasks due to varying levels of design quality. Figure 22 shows an example of the system dynamics model structure. For naval ship design, the system dynamics variable "initial work to be done" is equivalent to the number of design nodes within the design spiral. Productivity is the rate of design accomplishment consistent with the number of designers assigned to and the complexity of the task. Quality may be interpreted as the rate of design convergence (i.e. the quantity of tasks requiring re-iteration.) Undiscovered rework and rework discovery represent the analysis steps of the design spiral. Known rework and rework accomplishment represent subsequent iterations of the spiral.

For typical project management models, this system dynamics structure is the basic "engine" for process flow. The base structure is then adjusted systemically to account for the impacts of various project management policies. For example, manpower allocation, budget, scope changes, project schedule, overtime and others may introduce feedback effects on productivity, quality, and work to do. These structures are explored more fully in Chapter 5, Process Model Sectors.

As a basic system dynamics structure (or molecule[92]), it is possible to begin using this structure to analyze the naval ship design process. However, the design spiral, as presented above, does not completely capture the design process. It is necessary to understand that the spiral interpretation does not fully reflect the method of design used by engineers.[93]

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[91] David Brown, "Naval Architecture", Naval Engineers Journal, January 1993, pages 43-44.
[92] Jim Hines, "Molecules", a presentation to MIT-Sloan course Application of System Dynamics, Cambridge, MA, Spring, 1998.
[93] Tan and Bligh, "A New Approach to an Integrated CAD Method for Surface Ship Design", Naval Engineers Journal, January 1998, page 36-37.

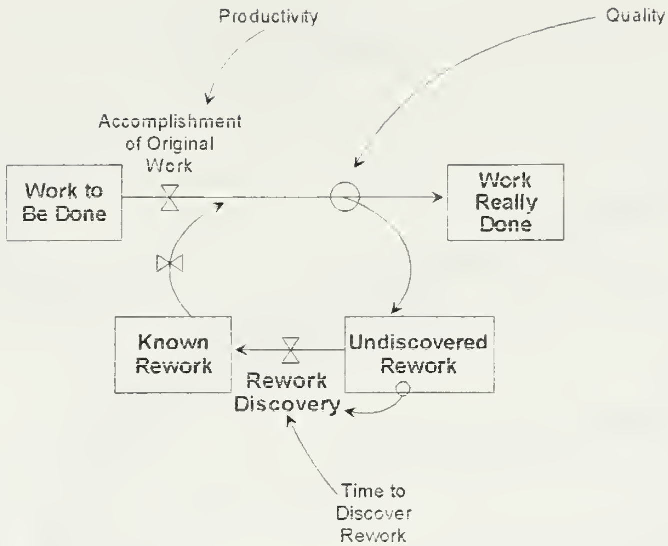

Figure 22 Generic System Dynamics Project Structure[94]

Consider a sampling of tasks for a typical ship design (Table 9 and Figure 23.) The listed tasks (arrangements, structural analysis, propulsion…) represent specific points on the design spiral. Note that the number of issues for each task element are not the same. Each iteration of the design spiral is not equivalent with respect to the tasks to be done. Additionally, the time duration of each issue that is performed during a design iteration is non-linear (note the numerous slope changes in both iteration duration and periods between tasks.) This indicates the order of tasks within the spiral is changing. The design spiral is not linear.

Task	Preliminary Design	Contract Design
General Arrangements	1250 Hours	3250 Hours
- General Arrangements Drawings	3 Issues	4 Issues
- Area/Volume Report	3 Issues	4 Issues
- Personnel Access Study	1 Issue	1 Update Issue
Structures	780 Hours	2140 Hours
- Midship Section	2 Issues	3 Issues
- Shell Expansion	1 Issue	3 Issues
- Calculation Report	1 Issue	2 Issues
Propulsion	1500 Hours	3520 Hours
- Machinery Arrangement Drawings	2 Issues	4 Issues
- Endurance Fuel Calculations	2 Issues	3 Issues
Etc…	Etc…	Etc…

Table 9 Sample Task Estimates for an Auxiliary Ship[95]

[94] James Lyneis, "Calibration of System Dynamic Models", a presentation to MIT-Sloan course Application of System Dynamics, Cambridge, MA, April 17, 1998.

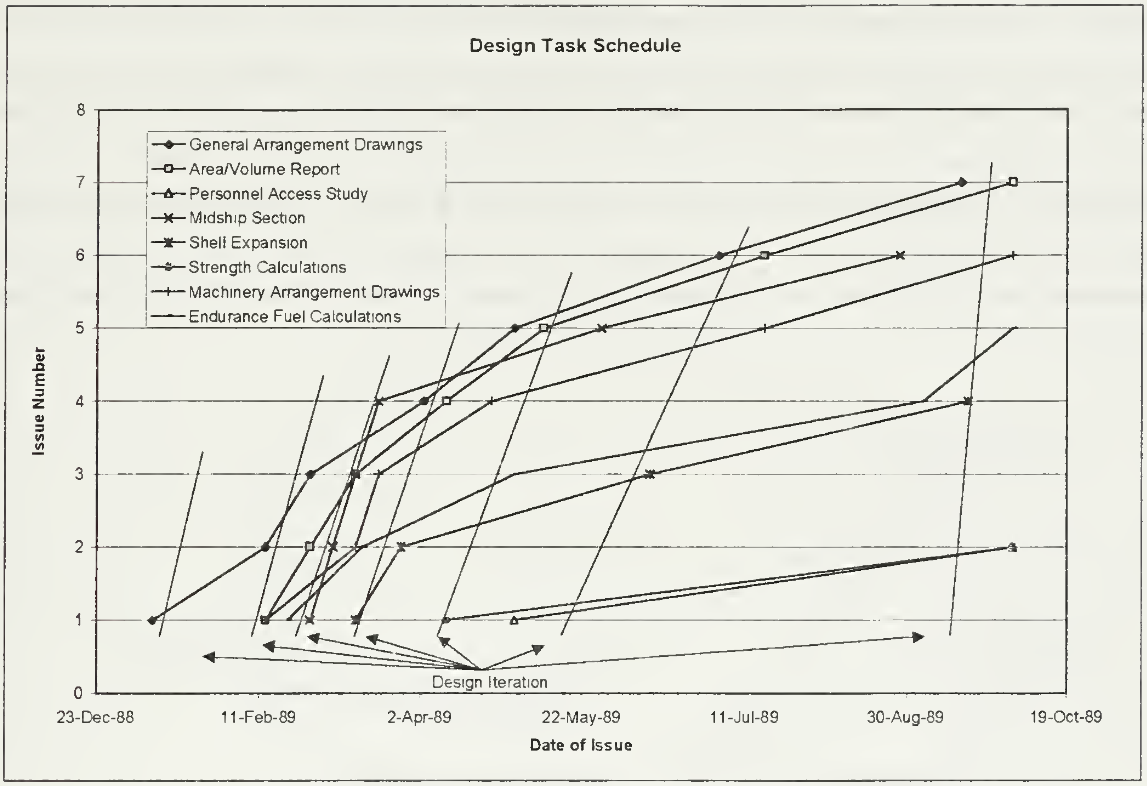

Figure 23 Sample Design Schedule Estimates for an Auxiliary Ship[96]

This is a fundamental shortfall in the spiral concept. The spiral portrays the design process as linear. This is not the case. The process is better described as "quasi-linear." The progression of tasks normally proceeds in a controlled, sequential manner. However, all design tasks within the spiral rely on input from and provide output to almost every other node of the process. As such, engineers and designers must have access to information (whether actual or estimated) from each design discipline and they must be acutely aware of the potential feedback effects caused by the changing output from their own design products. As a result of these interrelationships, the spiral is actually a network or "interaction mesh" joining design nodes by physical relationships and information flows.[97]

Take a simple example: power balance (Figure 24). Suppose the current iteration of a ship design does not achieve desired speed. The current hullform results in required horsepower for speed…approximately a cubic relationship. The required horsepower corresponds to a larger propulsion plant concept…a non-continuous step function. The propulsion plant requires a larger machinery volume and larger displacement… propulsion plant power density increases asymptotically. The hullform grows to accommodate larger propulsion stack length…volume growing as the cube of linear dimensional increases in plant size. Support systems also grow with the larger propulsion system and larger hullform…system weights increasing with hull parameters and propulsion plant horsepower. The larger hullform results in greater hull weight…hull weight increases as L^2-L^3 and hull

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[95] Ron Nix, "T-AG9X Preliminary/Contract Design Estimates", Naval Sea Systems Command, January 16, 1987.
[96] Ibid.
[97] David Brown, "Naval Architecture", Naval Engineers Journal, January 1993, pages 44-45.

surface area increases as L^2. The new hullform and displacement result in an increase in horsepower required for powering at the desired speed…hull resistance increasing in frictional resistance with increased displacement and varying in wave and residual resistance by the choice of hull parameters. The result: increasing power to achieve speed can result in a need to further increase power to achieve speed. The key to convergence of this process will depend on the relationship of the various non-linear parameters and the choices of designers to manage feedback of those parameters. Also, note that the design process is impacted by many of the disciplines of the spiral (marine engineering, hydrodynamics, structural engineering, weight engineering, etc.) and did so in a non-linear sequence.

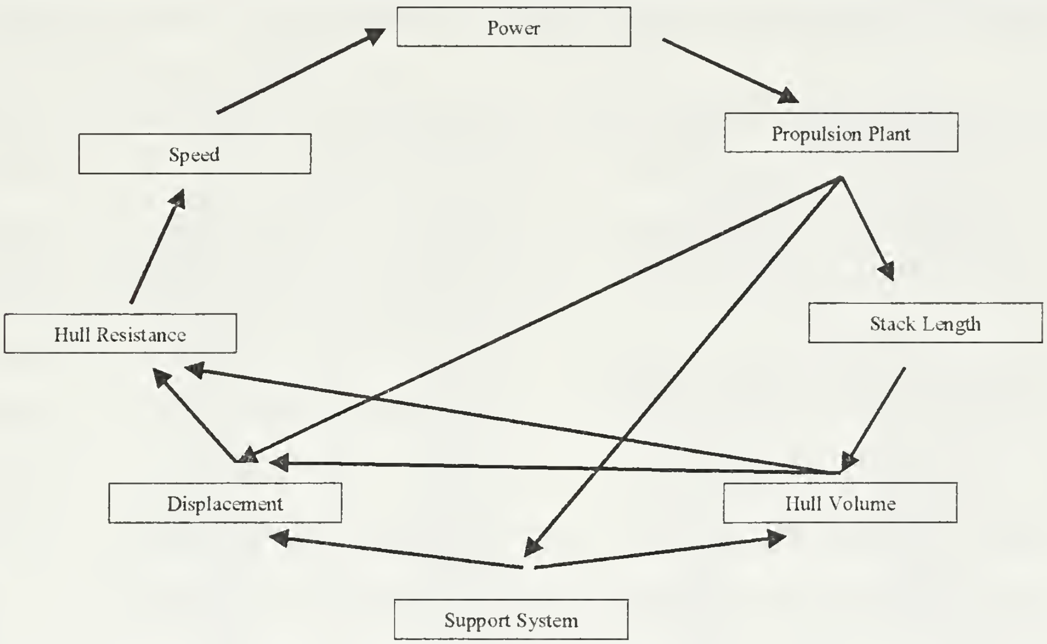

Figure 24 Simple Iterative Design Network

Another example of the design process as "quasi-linear" spiral is seen in the application of design synthesis software. The Advanced Surface Ship Evaluation Tool (ASSET) is a concept and preliminary design synthesis tool used by the United State Navy to balance and assess various naval ship concepts. The program is structured as presented in Figure 25. The figure shows how, like the spiral, ASSET proceeds sequentially through a series of design tasks (called modules) and iterates solutions for a convergent design. This progression leads to a linear view of the design process. Figure 25 also shows a sample of the master parameter list (MPL.) The MPL is a product model database containing all design attributes used as input and generated as output by the ASSET modules. It is the interaction of the sequential modules with the MPL that creates dynamic, non-linear design behavior similar to that seen in Figure 24.

To demonstrate this behavior, consider the analysis of the DDG-51 in ASSET. The baseline ship has four GE LM-2500 gas turbines propulsion engines with 19220.4 kW each. This results in a total shaft power of 74,974 kW and a resultant maximum speed of 31.2 kts. Suppose that a step decrease of propulsion power is proposed by replacing the current LM-2500 model 30 engines with smaller model 21 engines. The smaller engines provide 16032.5 kW each, 62,539 kW total shaft power and a maximum speed of 30.2 kts. The synthesis of this change

requires 5 iterations of the design in ASSET. During each iteration, the ASSET modules modify ship characteristics stored in the MPL and consider the characteristics non-convergent if the values change by more than 0.1% from the previous iteration. Table 10 lists those characteristics for each non-convergent iteration that posed the greatest differential from the previous iteration. Note that the appendage module converges faster then the others. Also, the auxiliary and weight modules are each limited by the same variable: lightship weight. The resistance module is most limited by effective horsepower (EHP) for only the first two iterations while EHP is most limiting to the machinery array for all iterations. Generally, the iterations demonstrate a variation of convergence rates among design disciplines, variations of limiting characteristics, and the coupling of design variables among disciplines. In other words, the process is non-linear.

Module	Iteration 1	Iteration 2	Iteration 3	Iteration 4
HULL GEOM	GMT	GMT	GMT	GMT
HULL SUBDIV	HULL ARR AREA AVAIL	SHAFT ALLEY VOLUME	SHAFT ALLEY VOLUME	SHAFT ALLEY VOLUME
DECKHOUSE	AREA BEAM	AREA BEAM	AREA BEAM	AREA BEAM
HULL STRUCT	HOGGING BM	MIDSHIP MOI	SAGGING BM	SAGGING BM
APPENDAGE	SKEG PROJ AREA	APPENDAGE DISP ARRAY		
RESISTANCE	SHIP EHP ARRAY	SHIP EHP ARRAY	PRPLN SYS RESIST ARRAY	PRPLN SYS RESIST ARRAY
PROPELLER	PROP RPM ARRAY	PROP RPM ARRAY	PROP RPM ARRAY	PROP RPM ARRAY
MACHINERY	SHIP EHP ARRAY	SHIP EHP ARRAY	SHIP EHP ARRAY	SHIP EHP ARRAY
AUXILIARY	LIGHTSHIP WT ARRAY	LIGHTSHIP WT ARRAY	LIGHTSHIP WT ARRAY	LIGHTSHIP WT ARRAY
WEIGHT	LIGHTSHIP WT ARRAY	LIGHTSHIP WT ARRAY	LIGHTSHIP WT ARRAY	LIGHTSHIP WT ARRAY
SPACE	DKHS ARR AREA REQ	OTHER ARR AREA REQ	OTHER ARR AREA REQ	OTHER ARR AREA REQ

Table 10 Limiting Characteristics for ASSET Iterations of a Propulsion Change to DDG-51

A similar non-linear representation of design synthesis can be found in other design tools: GODDESS (Government Defense Design for Ships & Submarines), CONDES (Concept Design Suite) and HFDS (Hull Form Definition System.)[98] Thus, like the basic design spiral described previously, seemingly linear structures for naval ship design synthesis are actually non-linear in nature.

[98] Whatmore and Wintersteen, A Review of Extant Design Tool Capabilities to Identify Common Design Tool for Future Collaboration, Naval Surface Warfare Center Carderock Division, Bethesda, MD, February 28, 1997.

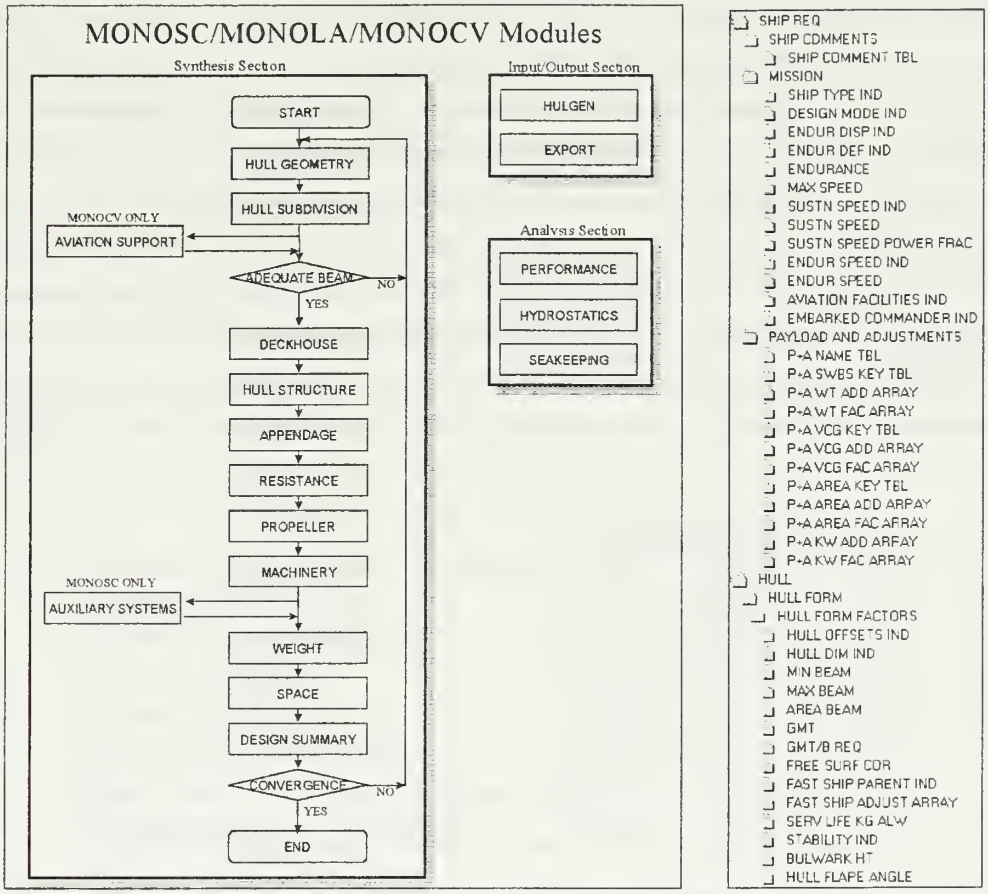

Figure 25 ASSET Program Structure and Master Parameter List Example[99]

In order to properly represent the naval ship design process in a system dynamics model, there must be an accounting of the non-linear interactions seen in the design spiral. A method that can capture this behavior is the Design Structure Matrix (DSM.)[100] First proposed by D. V. Steward in 1981, DSM is a graphically based technique to express design process information in a matrix form. The matrix structure shows design tasks by input and output relationships. These relationships can be found from physical requirements of engineering as well as procedural requirements and structures applied by design managers.

Consider the design tasks discussed previously (Table 9.) The tasks demonstrate a combination of sequential and concurrent relationships. These relationships can be captured in a matrix. A possible matrix formulation for the tasks is shown in Figure 26. The rows are tasks in the design sequence with the corresponding columns showing those fields that provide input to the task in the row. The diagonal is assumed to be "0" as a single task should not be dependent on itself (note that this assumption may not be correct if the design task is itself a compilation of smaller tasks.) Each matrix element is represented as binary. However, it is possible to further refine the "strength"

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[99] Naval Surface Warfare Center Carderock Division, "Getting Started & Tutorials: Advanced Surface Ship Evaluation Tool (ASSET) Family of Ship Design Synthesis Programs", September 30, 1997, page 3-29 and page 3-22.

[100] Eppinger, Whitney, Smith and Gebala, "A Model-Based Method for Organizing Tasks in Product Development", Working Paper, Massachusetts Institute of Technology, 1993.

of relationships by a percentage of input information required, differential change of dependent row on input column or other order of magnitude measure.[101] Ideally, the sequence of rows should form a lower triangle, thus showing that tasks proceed sequentially from previous tasks. However, the non-linear relationships of the naval ship design process result in both upper and lower triangle relationships...this is called couple development. The ability to perform effective concurrent engineering (i.e. maximize productivity and minimize rework) is dependent on the level of coupled development, the strength of those relationships, and the ability of engineers to select design lanes (initial design assumptions) that minimize iteration differentials. It is further possible to optimize a process by rearranging task sequences to minimize the upper triangle against the lower. Such optimization is particularly useful for reduction of design code, computational effort and design effort in synthesis of naval ship designs.[102] Overall, DSM combined with a system dynamics model provides an effective means to represent naval ship process dynamics.

		1	2	3	4	5	6	7	8
General Arrangement Drawings	1	0	1	1	0	0	0	1	1
Area/Volume Report	2	1	0	0	0	0	0	1	1
Personnel Access Study	3	1	1	0	0	0	0	1	0
Midship Section	4	1	0	0	0	1	1	0	0
Shell Expansion	5	0	1	0	1	0	1	0	0
Strength Calculations	6	0	0	0	1	1	0	0	0
Machinery Arrangement Drawings	7	1	1	0	0	0	0	0	1
Endurance Fuel Calculations	8	0	1	0	0	0	0	1	0

Figure 26 DSM for Sample Design Tasks

4.2 Design Disciplines

With an enhanced understanding of the design spiral, it is necessary to restructure the basic system dynamics project management structure to reflect the non-linear process seen in the DSM structure. Additionally, it is necessary to structure the design tasks in a manner that appreciates the multitude of design disciplines applicable to the design process and subsequent task accomplishment, without requiring a level of detail that precludes effective understanding and exploration (i.e. minimize the DSM structure.) Specifically, the structure must reflect the variety of design tasks within a single phase, the inter-relationships of those tasks, and the growth of tasks (as a function of necessary design detail) from phase to phase.

A causal loop diagram is developed to understand the structure that must be included in a naval ship design model. Consider the following situation:

1. Initial iteration begins with a quantity of design tasks,

[101] Ibid.

[102] Tan and Bligh, "A New Approach to an Integrated CAD Method for Surface Ship Design", Naval Engineers Journal, January 1998, page 35.

2. Engineers and managers with specific knowledge of their design disciplines must communicate information related to their design tasking to the group in order to provide dependent design tasks with input data (establishing design lanes),
3. Based on the level of organizational communication (ranging from disconnected to fully integrated design teams) and the imposed design constraints (such as design requirements and design margins), an engineer find that the initial assumptions made to proceed with the design may or may not be accurate at the end of the design iteration
4. As a result of interaction…if communication is lacking or the design is not sufficiently constrained, then the design tasks may be delayed due to competing variations in the initial design assumptions or fail entirely due to divergent tasks coupling.

Figure 27 demonstrates this concept graphically.

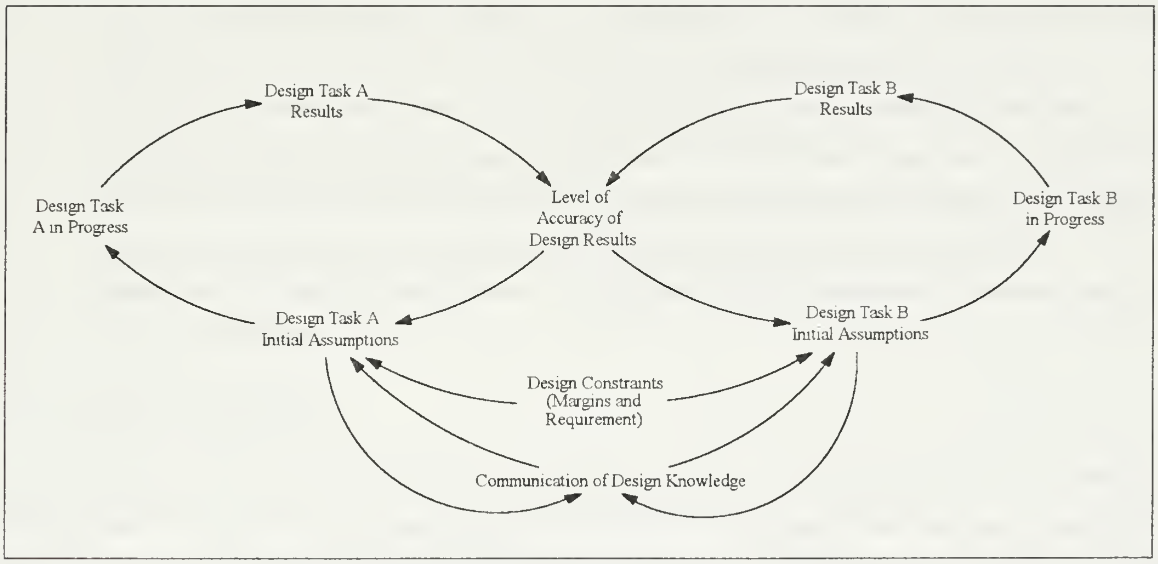

Figure 27 Generic Design Task Relationship

The rate of design communication and, thus, the rate of design iterations is composed of both controlled iterations or "baseline freezes" (those designated instances in the design process during which all design elements are frozen to a common set of values) and free iterations (those communications of design change resulting from the direct communication of engineers or exchange of design characteristics with a common design product model.) "Baseline freezes" typically occur at predictable rates. An example of the these rates are shown in Table 11. A baseline freeze represents a complete design spiral and, thus, a complete ship design; but a completed spiral may not represent a fully balanced or optimized design. Within the context of DSM, a baseline freeze would be a complete sequencing through the design task matrix. Free iterations occur due to coupled development. Designers from a dependent task group communicate at some rate with other task groups and update information to maintain accurate task data. A slow communication rate will naturally delay the design process. This fact has been noted by the method of "over the wall" design. However, communication at too quick a rate could be equally concerning. Specifically, an increased rate results in increased communication overhead. Increased communication may result

in decreased time for productive engineering activities. Additionally, high variations in input data can result in instabilities in convergence rates. Iteration rates and communication rates impact the design model.

Design Phase	Typical Number Iterations	Typical Duration
Concept Design Phase	10-100	3-5 days
Preliminary Design Phase	4-8	3-6 weeks
Contract Design Phase	2-4	1-3 months
Detailed Design Phase	1-2	1-3 years

Table 11 Typical Design Iteration Issues and Durations[103]

Based on this behavior, it is possible to model the cycle time relationship of task accomplishment with respect to design interactions. The following assumptions apply to the development of the relationships:

- Only first order relationships are modeled (i.e. hull performance is a function of hull geometry, but only through the first order translation of hull geometry into seakeeping and resistance attributes)
- Relationships are considered binary (1 or 0) regardless of the degree of relationship. However,
- Relationships judged as existent (1) must be supported by direct physical properties (i.e. SWBS Group 100 Weight is a direct function of Hull Geometry parameters and Structural dimensions) or legal and management requirements (i.e. all aspects of the design process must provide inputs to the programmatically managed design history.) See Chapter 8.4 for a complete list of references used to develop relationships.

4.3 Design Task Matrix

Given the non-linearities of the design spiral and the vast quantity of design tasks accomplished during a naval ship design (a typical surface combatant design may have over 2,500 separate ship drawings in detail design alone), it is necessary to aggregate the tasks into appropriate design nodes. Aggregation allows analysis of dynamic interactions and concurrency relationships relative to the design process, while maintaining manageable quantity and quality for modeling. An analysis of design products (see Chapter 8.4) required at each phase of design (concept through manufacturing) and for each system discipline shows that the system disciplines can be grouped into 6 nodes and 23 sub-nodes. Table 12 shows a listing of the nodes, sub-nodes and a designation code that will be used throughout the remainder of this work and the design model to refer to the nodes.

[103] Extrapolated from interviews (see Chapter 8.2) and basic design resources (see Chapter 8.4).

Designation	Node	Sub-Node
A0	Programmatic Disciplines	
A1		Program Management Tasks
A2		Requirements & Assessment Tasks
A3		Risk Mitigation & Coordination Tasks
B0	Systems Engineering	
B1		Logistics & Reliability Engineering
B2		Design Integration & Specifications
B3		Producibility & Production Engineering
B4		Performance & Requirements Engineering
B5		Manning
C0	Hull Systems Engineering	
C1		Hull Geometry
C2		Weight & Stability Engineering
C3		Hydrodynamics-Resistance
C4		Hydrodynamics-Seakeeping
C5		Hydrodynamics-Maneuvering & Appendages
C6		Structural Engineering
C7		Space & Arrangements
D0	Machinery Systems Engineering	
D1		Machinery Systems Design & Integration
D2		Propulsion Systems
D3		Electrical Systems
D4		Auxiliary & Support Systems
D5		Deck, Handling & Aircraft Support Systems
E0	Mission Systems Engineering	
E1		Mission Systems Selection, Design & Integration
E2		Topside Design & Integration
F0	Cost Engineering	
F1		Cost Estimation & Analysis

Table 12 Design Process Nodes and Sub-Nodes

Node	Task Element	Node	Task	A 1	A 2	A 3	B 1	B 2	B 3	B 4	B 5	C 1	C 2	C 3	C 4	C 5	C 6	C 7	D 1	D 2	D 3	D 4	D 5	E 1	E 2	F 1
Programatic	Program Management Tasks	A	1	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
	Requirements & Assessment	A	2	1	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
	Risk Mitigation & Coordination	A	3	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Systems Engineering	Logistics and Reliability Engineering	B	1	1	1	1	0	1	0	0	1	0	0	0	0	1	1	1	1	1	1	1	1	1	1	0
	Design Integration & Specifications	B	2	1	1	1	0	0	1	0	1	1	1	0	0	1	1	1	1	1	1	1	1	1	1	0
	Producibility and Production Engineering	B	3	1	1	1	1	1	0	0	0	1	1	0	0	1	1	1	1	1	1	1	1	1	1	0
	Performance-Requirements Assessment	B	4	1	1	0	1	0	0	0	1	0	1	1	1	1	1	1	1	1	1	1	1	1	1	0
	Manning	B	5	1	1	1	0	0	0	1	0	0	0	0	0	0	0	1	1	1	1	1	1	1	1	0
Hull Engineering	Hull Geometry	C	1	1	1	1	0	0	0	1	0	0	1	1	1	1	0	1	1	1	1	1	1	1	1	1
	Weight, Hull Subdivision & Hydrostatic Design	C	2	1	1	0	0	0	0	1	0	1	0	0	1	1	1	1	1	1	1	1	1	1	1	1
	Hydrodynamics-Resistance	C	3	1	1	0	0	0	0	0	0	1	0	0	0	1	0	0	0	1	0	0	0	0	1	0
	Hydrodynamics-Seakeeping	C	4	1	1	0	0	0	0	0	0	1	1	1	0	1	0	0	0	0	0	1	0	0	0	0
	Hydrodynamics-Maneuvering, Appendage & Propeller Design	C	5	1	1	1	0	0	0	1	0	1	1	0	1	0	0	0	0	1	0	1	0	0	0	0
	Structures-Static and Dynamic Design	C	6	1	1	1	0	0	0	1	0	1	1	0	1	1	0	1	1	1	1	1	1	1	1	1
	Space and Arrangements	C	7	1	1	0	0	0	0	1	1	1	1	0	0	1	1	0	1	1	1	1	1	1	1	1
Machinery Systems Engineering	Machinery Systems Design and Integration	D	1	1	1	1	0	0	0	1	1	1	1	1	0	1	0	1	0	1	1	1	1	1	1	1
	Propulsion Systems	D	2	1	1	1	0	0	0	1	0	1	1	1	0	1	0	1	1	0	1	1	0	0	0	1
	Electrical Systems	D	3	1	1	1	0	0	0	1	1	1	1	0	0	1	0	1	1	1	0	1	1	1	1	1
	Auxiliary and Support Systems	D	4	1	1	1	0	0	0	1	1	1	1	0	0	1	0	1	1	1	1	0	1	1	1	1
	Deck, Handling and Aircraft Support Systems	D	5	1	1	1	0	0	0	1	0	0	1	0	1	0	0	1	1	0	1	1	0	0	0	1
Mission Systems Engineering	Mission Systems Selection, Design and Integration	E	1	1	1	1	0	0	0	1	0	0	1	0	1	0	0	1	0	0	1	1	0	0	1	1
	Topside Design and Integration	E	2	1	1	1	0	0	0	1	0	0	1	0	0	0	0	1	0	0	1	1	0	1	0	1
Cost	Cost Estimates & Analysis	F	1	1	1	1	0	0	1	0	1	1	1	0	0	1	1	1	1	1	1	1	1	1	1	0

Figure 28 Task Interaction Matrix

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Analysis of the relationships of these task elements results in the DSM design matrix shown (Figure 28.) Figure 29 shows a complete network resulting from the matrix relationships. The outer ring of the network represents the traditional, linear design spiral. The interactions represent the range of free iterations possible in the process. Chapter 5 discusses the specific approach used to combine the system dynamics process model with the DSM model. The remainder of this chapter addresses the logic supporting the DSM elements and the expected behavior resulting from the elements and nodes.

Before preceding, note that the following assumptions have been made with respect to the DSM structure:

- The baseline task elements (**Table 14** through Table 38) are specific to the DDG-51 program. As such, elements for current surface combatant design programs may not be represented.
- The discussions associated with each task node (Sections 4.4 through 4.9) provides a justification for the DSM relative to the DDG-51 task elements as well as highlighting current trends in tasks and interdependencies. Future applications of the DSM structure must incorporate dependency shifts resulting from those trends.

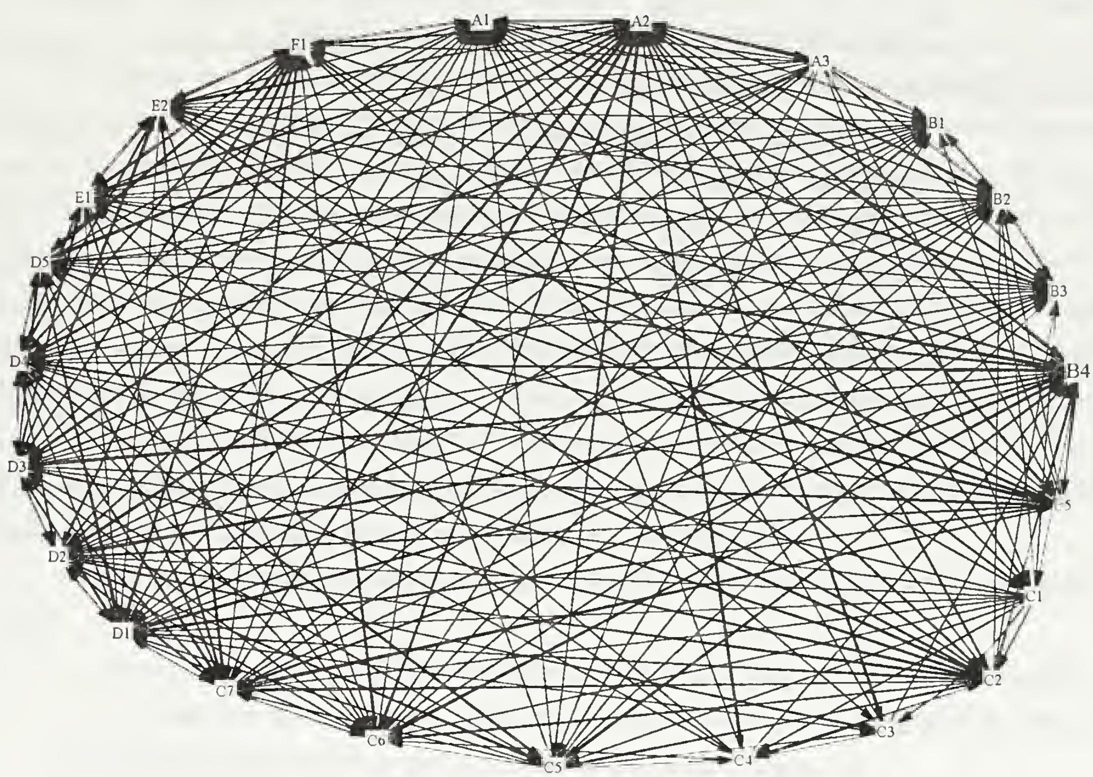

Figure 29 Design Spiral "Interactions"

4.4 Programmatics

Programmatics represents the core tasks of every naval ship design project. It may also be referred to as Acquisition Management. Programmatics contains tasks related to Program Management, Requirements Setting and

Assessment, and Risk Mitigation and Coordination. These elements support the creation of a design and acquisition program, management of the design and contract award, oversight of the production design and construction, and engineering support to the operational forces throughout the life cycle of the ship. Specific programmatic tasks are required by DoD Instruction 5000.2 (Defense Acquisition Management Policies and Procedures) and DoD Manual 5000.2 M (Defense Acquisition Management Documentation.) A complete listing of applicable directives is found in the Defense Acquisition Deskbook (http://www.deskbook.osd.mil.) Additionally, tasks are necessitated by good engineering and business practice such as maintaining a design history or managing scope growth.

The elements of programmatics were under fire in recent years due to perceived inefficiencies. As the fundamental decision-making support systems, programmatic tasks have seen a natural growth in project deliverables. This growth correlates to increasing technological design risk and pressure to decrease design cost (see discussion of externalities in Chapter 2.) The result is increasing time required to prepare documentation (Table 13.) Figure 30 shows task efforts (averages for 45 Navy, ACAT I design programs) expended for key programmatic deliverables. As the key inputs to program milestones, there has traditionally been a need to produce significant portions of these documents prior to each review stage, which may include as many as ten different review and approval levels.[104] The combination of multiple decision layers and increasing programmatic efforts is viewed as a key factor contributing to the growth of the design cycle.

Ship Program	Preliminary Design	Contact Design
DDG-993	N/A	1,454
CG-47	1,818	8,147
DDG-51	2,696	23,654

Table 13 Programmatic Man-hour Effort Trends[105]

[104] William Ball, "DoD Acquisition Policy and the Effect on Naval Ship Design", Society of Naval Architecture and Marine Engineering, February 25, 1992, page 7-5.
[105] Ship Design Group, Ship Design Project Histories: Volume I, II and III, Naval Sea Systems Command, September 1978, May 1986 and August 1996.

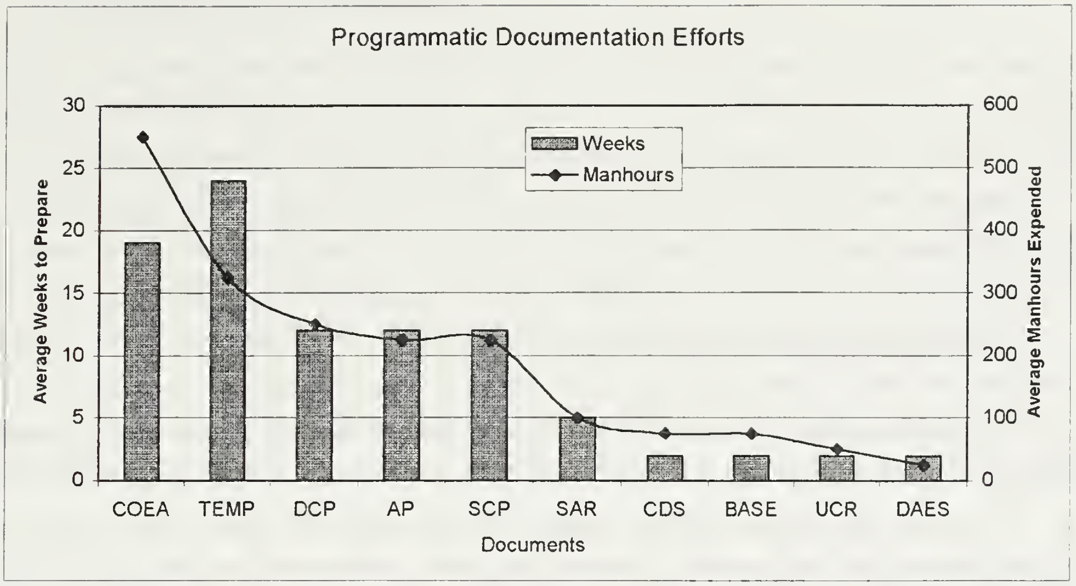

Figure 30 Average Programmatic Documentation Effort[106]

To counter these trends, significant changes were implemented with respect to programmatics. As part of acquisition reform initiatives (see Chapter 1.1.1), contract specifications, programmatic deliverables and design reviews were modified to remove redundancies and outdated requirements. In particular, program managers are granted greater authority to reduce documentation requirements and waive redundant design reviews entirely. These changes have significant impacts (positive and negative) on design programs. For instance, the LPD-17 contract design effort was negatively impacted when a directive to reduce contract specifications was implemented well into the design process. Although the effort reduced contract deliverables (reduction from 1,452 to 327 specifications), thus improving efficiency in lead ship design, contract design efforts were delayed several months to implement the reform (the effort was referred to as "triage".)[107] Conversely, reforms allow programs, such as the current DD-21 program, to realize improved management efficiency and reduced review periods.[108] These cases indicate that implementation of programmatic reforms may dynamically impact a project.

In order to simulate programmatic fluctuations within the design model, the following assumptions will be made:

1. Total programmatic requirements (number of tasks at each design phase) are fixed initially for the model
2. A capability to generate random and/or specified growth and decay of programmatic tasking is included.

Values for baseline productivity and task levels are provided in Chapter 8.5.

[106] RADM Roger B. Horne, "Concept to Commissioning, Improving the Ship Design, Acquisition and Construction Process: Strategic Plan", Naval Sea Systems Command, Washington, DC, June 1991, III-2.3.11.
[107] Fireman, Fowler, McIntire and Wilkins, "LPD 17: In the Midst of Reform", Naval Engineers Journal, May 1995, page 267.
[108] CAPT Dennis Mahoney (USN), former DD-21 Program Manager, interviews during Spring 1998.

4.4.1 Program Management Tasks

Program management centers on five key areas: planning, controlling, organizing, staffing and leading. Planning includes all those activities associated with the acquisition strategy and program schedule. The major task element for program management in a modern ship design program is the Acquisition Program Baseline (APB). The APB establishes the metrics to measure performance, cost and schedule for the acquisition program and includes objective and threshold components. The APB is a living document that is adjusted and acted upon based on the influence of design changes, warfare requirements and schedule pressures. The APB is the primary documentation for review and approval (SAR and DAES.) The APB development and approval process is demonstrated in Figure 63. Specific instructions for preparation of the APB are found in DoD Directive 5000.2.

Controlling tasks are those elements necessary to monitor conformance of program performance to the guidance of authorities and the APB. The use of Cost/Schedule Control System Criteria (C/SCSC) may be utilized to "detect a deviation from the plan, (activate) a control mechanism to bring the system back into line."[109] Specifically, controlling requires continual audit of program processes to monitor and correct process performance.

Organizing and staffing involve the management of personnel and manpower budgets with respect to the design process needs. This is a major systemic force in the design process. As such, it is explicitly modeled beyond tasking requirements (see Chapters 5.4 and 5.5.)

Finally, leadership is the major function of the program management staff. The ability to clearly communicate desired program direction, goals and needs is critical to program performance. Leading the program entails continuous information gathering and evaluation with respect to the forces acting to control the program (see Chapter 2). As a result of the program managers perceptions of those forces, he or she must respond by marketing the good aspects of the program and addressing concerns to responsible authorities. In a teaming environment, as proposed by IPPD/IPT, program leadership means the ability to establish and maintain consensus. A program manager is by definition the leader of the design program, and it is his or her continuous role (and thus tasking) to lead and guide a successful acquisition program. To implement leadership over all aspects of the project, program management will naturally require input and output connections to all design disciplines

[109] Defense Management College, "The Program Manager's Notebook", Fort Belvoir, VA, June 1993.

Task Element	Concept	Preliminary	Contract	Detailed			
				Functional	Transition	Zonal	Production
Acquisition Program Baseline (AP)	1	1	1	1	1	1	1
Acquisition Strategy	1	1	1	1	1	1	1
Acquisition Decision Memorandum (ADM) & Defense Acquisition Executive Summary (DAES)	1	1	1	1	1	1	1
Program Management	1	1	1	1	1	1	1
Milestone Preparation and Exit Criteria Satisfaction	1	1	1	1	1	1	1
Security & Security Protection Strategy	1	1	1	1	1	1	1
Legal Issues Analysis	1	1	1	1	1	1	1
Treaty Compliance Assessment	1	1	1	1	1	1	1
SHAPM Support & Special Studies		1	1	1	1	1	1
Design History		1	1	1	1	1	1
Design Site Management			1	1	1	1	1
Hull Engineering Task Group Support			1	1	1	1	1
Machinery Task Group Support			1	1	1	1	1
Design Control					1	1	1

Table 14 Program Management Tasking

Based on analysis of the DDG-51 program and other surface combatant projects, a general listing of program management tasks is developed.

Table 14 shows the appropriate design phase during which specific program management tasks are activated. It is assumed that tasks are updated at each design stage. **The list is not all-inclusive** (nor are later lists in this chapter), but does represent those primary task elements required by directive or good engineering and management practice (see Chapter 8.5.) For purposes of the design model, the given quantity of tasks (along with total programmatic man-hours expended) provides sufficient aggregate detail to model process behavior. With respect to the DSM structure, the command and control nature of program management necessitates complete input from and output to all design disciplines. As such, the row and column is unity (see Figure 28.)

4.4.2 Requirements Setting and Assessment

The second program task element is the interface between the designers and the warfighters: requirements setting and assessment. The primary concern of requirements is the definition of the defense-technical problem and translating this problem into a potential design. Chapter 1.1.2 specifically addresses the current mechanisms being applied to improve problem definition and translation. Additionally, there are a number of specific design deliverables that relate to those mechanisms. The Mission Need Statement (MNS) and Operational Requirements Document (ORD) are the initial documents produced in this discipline. The MNS in a non-system specific statement of operational capability. The ORD formally states warfighter objectives and minimum acceptable requirements for operational effectiveness of a proposed ship concept and its associated systems. Based on the requirements of the MNS and ORD, an AoA (formerly COEA) study is performed to analyze potential system options satisfying the requirements. The AoA as defined here is not the act of concept engineering analysis, but rather the accumulation of information developed by specific engineering disciplines in response to the stated needs of the MNS and ORD. In other words, the AoA is a document or task requirement, not a process. Instead, concept and preliminary design are the processes by which AoA tasking is implemented. Figure 61, Figure 62, and Figure 64 show specific processes by which these documents are prepared and reviewed. These requirements and post engineering assessments are continually audited to ensure the design meets the needs of operational forces.

When deficiencies are discovered, the program manager has three primary options: modify the mission requirements, re-initiate the design to achieve the stated need, or introduce an engineering change to achieve the stated need. Modification of mission needs is a relatively detailed process, but can be effective in the very early stages of design. This is particularly true during concept design if the design community (in conjunction with AoA tasking) is given an opportunity to present operational forces with specific design trades enabled by requirement changes. The approaches presented in Chapter 1.1.2 demonstrate the effectiveness of this approach. If operational needs cannot be changed, then the design may need to be re-initiated. There are numerous examples of this approach in the last few years as a result of changes in defense doctrine and force structure. For instance, the DDG-51 Flight IIA program is a direct result of a need to produce substantial improvements to the DDG-51 program following decommissionings of numerous combatant ship classes during the early 1990's. This option is not practical unless the design process is still young (the DDG-51 concept design process lasted four years for this reason) or the requirements changes preclude reasonable design modification within the current program (DDG-51 Flight IIA.) When changes are moderate, then engineering change proposals (ECPs) may be used. Once again, early introduction of ECPs is preferred. Due to the long duration of naval ship design projects, it is inevitable that changes are required. These changes have well documented negative impacts on the design process (see Chapter 1.1.2.) There are methodologies which can minimize the impact of design change including: Open Architecture and Modularity.[110] Ultimately, the program manager must decide whether the timing and performance gains of a given design change outweigh the impacts to schedule and cost.

For the purposes of the naval ship design model, these tasks and behaviors are incorporated as follows:

1. Tasks profiles are set per those listed in **Table 15**
2. ECPs are introduced by random and/or specified task growth to the initial tasks
3. The fraction of task growth from ECPs is directly determined by the first order impacts of the scope growth being introduced (i.e. a design with open architecture would see a substantially smaller task fraction increase than a design without change mitigation mechanisms.)

Like the structure for program management, requirements setting indicates a direct output to all design tasks and assessment of those requirements requires input from all tasks. Thus, the DSM structure is fully populated.

Task Element	Concept	Preliminary	Contract	Detailed			
				Functional	Transition	Zonal	Production
Decision Coordination Paper (DCP)	1	1	1	1	1	1	1
Selected Acquisition Report (SAR)	1	1	1	1	1	1	1
Congressional Data Sheet (CDS)	1	1	1	1	1	1	1
Mission Need Statement	1	1	1	1	1	1	1
Operational Requirments Document (ORD) & Requirements Setting	1	1	1	1	1	1	1
System Concept Paper (SCP) & Design Review/Report	1	1	1	1	1	1	1
System Threat Assessment	1	1	1	1	1	1	1
COEA/Analysis of Alternatives	1	1	1	1	1	1	1
Engineering Change Proposals (ECP) & "External" Change Requests						1	1

Table 15 Requirements Setting and Assessment Tasks

110 MIT Course 13.64, "CVX Product and Process Planning", Massachusetts Institute of Technology, Cambridge, MA, Summer 1997, page 70.

4.4.3 Risk Mitigation and Coordination

The final category of programmatics is that set of tasks which provides analysis of potential program risks and coordinates technology development with other defense programs. Primary tasks in this category are: Development Test and Evaluation (DT&E), Test & Evaluation Master Plan (TEMP), Live Fire Test & Evaluation (LFT&E) analysis, Safety analysis and coordination efforts for Research, Development, Test and Evaluation (RDT&E). DT&E determines the potential variability in effectiveness, cost and schedule associated with technologies under consideration for the design. If the technologies are too risky for consideration, fall-back options are explored to allow the design to proceed. DT&E changes can impact the design rates through the introduction of delayed tasks (technologies maturing behind schedule) or scope change (transition of the program to the fallback position or introduction of a newly maturing technology.) Even after specific technologies are introduced into the design, it is necessary to develop a schedule to evaluate the effectiveness of the technology as integrated in the ship design. Specifically, the TEMP and LFT&E provide the structure to test system effectiveness. As known and perceived risks relative to the technology or capability are disclosed, the plans must adapt. An increasingly important method of risk reduction is coordination of RDT&E with other programs. In particular, early R&D projects must be monitored to ensure compatibility with ship design development and mission needs. For more advanced technology programs, Ship Acquisition Managers (SHAPMs) must coordinate efforts with Participating Managers (PARMs). Once again, changing technology schedules and capabilities may impact the design process.

Task Element	Concept	Preliminary	Contract	Detailed			
				Functional	Transition	Zonal	Production
Risk Assessment	1	1	1	1	1	1	1
Programmatic Measures of Effectiveness Analysis (Cost, Schedule & Performance Risk Analysis)	1	1	1	1	1	1	1
DT&E Report	1	1	1	1	1	1	1
Environmental, Safety & Health Evaluation	1	1	1	1	1	1	1
Technology & Industrial Capability Assessment (Commercial & NDI Evaluation & Status)	1	1	1	1	1	1	1
Cooperative Opportunities Assessment	1	1	1	1	1	1	1
Integrated R&D	1	1	1	1	1	1	1
Test & Evaluation Master Plans (TEMP)	1	1	1	1	1	1	1
LFT&E Waiver Certificate	1	1	1	1	1	1	1
LFT&E Report	1	1	1	1	1	1	1
Computer Applications & Support, Information Technology Architecture	1	1	1	1	1	1	1
Information Technology Statutory Compliance (Information Technology Management Reform Act (ITMRA), Government Performance and Results Act (GPRA), Paperwork Reduction Act (PRA))	1	1	1	1	1	1	1
System Safety Study		1	1	1	1	1	1

Table 16 Risk Mitigation and Coordination Tasks

For the purposes of the naval ship design model, these tasks and behaviors are incorporated as follows:

1. Tasks profiles are set per those listed in Table 16
2. Changes resulting from technology changes are introduced by random and/or specified task growth to the initial tasks

The DSM structure for risk mitigation deviates slightly from previous programmatic tasks. Process flows indicate that although risk tasking is performed for specific engineering disciplines (hull, machinery, payloads, system, cost), the risk analysis information is delivered through program management and requirements rather than directly to the responsible disciplines. In this manner, risk mitigation and coordination acts as an information

control gate during feedback of design attributes. As assessments of requirements against presented design parameters are assimilated, the elements of risk mitigation incorporate those values. If specific risk analysis indicates concerns or necessary coordination, then modifying information will flow back to those disciplines that perform physical design (hull geometry, mechanical systems, mission systems, etc.)

4.5 Systems Engineering

The second design process node is systems engineering. It is important to differentiate systems engineering as discussed in Chapter 3 from this process node. System engineering as discussed previously represents the overarching optimization of cost, effectiveness and schedule to meet a need. In this context, the naval ship design process is a subset of systems engineering. However, within naval ship design is an alternative systems engineering definition. In this context, systems engineering represents those engineering disciplines required to integrate specific ship design components (hull systems, mechanical systems, and combat systems), to analyze the integrated components in the system (Integrated Logistics Support (ILS), contract specifications, producibility, manning) and to compare the system performance against requirements (mission effectiveness.) In this context, systems engineering has evolved over the last 40 years to become a key element of the design process. Initial formalization of systems engineering began in the 1950's on the first ballistic missile programs. During the 1970's, systems engineering achieved true maturity in the Aegis Weapons Program (1970's) under the guidance of ADM Wayne Meyers (USN retired.) During an interview with ADM Meyers[111], he made the following comments regarding the impacts of systems engineering on the overall design process:

1. "Warships are inherently inefficient design exercises." Due to the scope of surface combatant design projects, individual design components are rarely optimized in the context of system impacts. For instance, component optimization generates vast numbers of supplier-vendors. A large vendor base requires complex supply chains which de-optimize ILS and life cycle cost. Until effective system optimization is realized (see Chapter 1.1.2), component development will continually generate divergences in systems development.
2. "Program managers don't know, only perceive, the true status of the fiscal, technical, temporal vectors." The goal of the program manager is to focus the project towards convergence. However, uncertainties in information, variations in cost, and delays in progress cause the vectors to diverge. In systems engineering, this is even more critical as the integration of components is constantly varying with the variable schedules and complexities of those components (Figure 23 and Table 9.) Coupled productivity and varying development rates produce delays in systems development.
3. "Knowledge…Engineering, Cost, etc…must be accumulated and tapped to facilitate systems integration." Systems engineering is the cap-stone of the naval engineering process. To effectively pull together the elements of the system, time and patience are necessary. Unfortunately, time is also the enemy of the design process…time generates changing requirements and changing technologies. To

[111] ADM Wayne Meyers (USN retired), interview on November 14, 1997, Arlington, VA.

understand systems engineering one must acknowledge the impact of time…early work is undone, later work will require iteration back to the component level, and very late work will introduce scope increases which can diverge the program.

Baseline (DDG-51) task levels and productivity levels for Systems Engineering are presented in Chapter 8.5.

4.5.1 Logistics and Reliability Engineering

Integrated Logistics Support (ILS) and Reliability, Maintainability and Availability (RMA) assessment are the disciplines that may most greatly determine the life cycle cost and operational effectiveness of the ship design. ILS is a management and technical approach that integrates support considerations into system and equipment design. Support requirements are determined by readiness objectives, current and planned supply chains (underway replenishment, storage, supply overhead, packaging, handling), maintenance plans, manning levels, and training pipelines. RMA (also known as RAM) is a complement to ILS. RMA analysis determines the level of ILS required. Specifically, RMA assesses operational functionally for the ship, redundancy versus reliability, and the ease of recovery of systems that do fail (relative to ILS and maintainability.)

Task Element	Concept	Preliminary	Contract	Detailed			
				Functional	Transition	Zonal	Production
Integrated Logistic Support & Maintenance Analysis	1	1	1	1	1	1	1
Reliability, Maintainability and Availability (RMA) Assessment	1	1	1	1	1	1	1

Table 17 Logistics and Reliability Engineering Tasks

RMA and ILS are highly coupled disciplines. As such, it is not unreasonable to assign a value of 1 to the diagonal for DSM (see Chapter 4.1.) However, the value of 0 is assigned to maintain consistency with DSM methodology. Input values are required from those disciplines that impact maintenance, reliability and support including: requirements, manning, hull structures, arrangements, mechanical and mission systems. The results of ILS and RMA feed programmatics for action, if necessary. Additionally, results provide input to producibility (ILS has a first order impact on production methods) and to performance (RMA is an input for Ship Vulnerability Modeling (SVM) and operational effectiveness measures.)

As would be expected, ILS and RMA should be started from the initiation of the design in order to achieve the greatest leverage over life cycle cost (LCC). Table 17 shows the progression of ILS and RMA tasks. Past design programs minimized the early ILS and RMA effort. This can be seen by the small man-months per task during concept and preliminary design shown in Chapter 8.5. Given current ILS trends, there is increased need for early analysis. Figure 31 shows the exponential growth experienced in ILS overhead measured as increasing parts listings (APL's.) With increasing parts and supply trains, ILS becomes an increasingly greater fraction of LCC. As shown in Figure 32, the primary ILS components (manning and maintenance) constitute almost 60% of the LCC. Recent efforts to counter the trend (such as Affordability Through Commonality (ATC) and open systems architecture) show promise. Applied to current design programs, these efforts provide substantial cost savings, but require greater man-hour efforts in early design. For the baseline design model, DDG-51 ILS task efforts are used. However, future "what-if" scenarios should reflect increased efforts in early stage design. This would provide program managers with a comparison of life cycle cost savings versus the impact on schedule and resources.

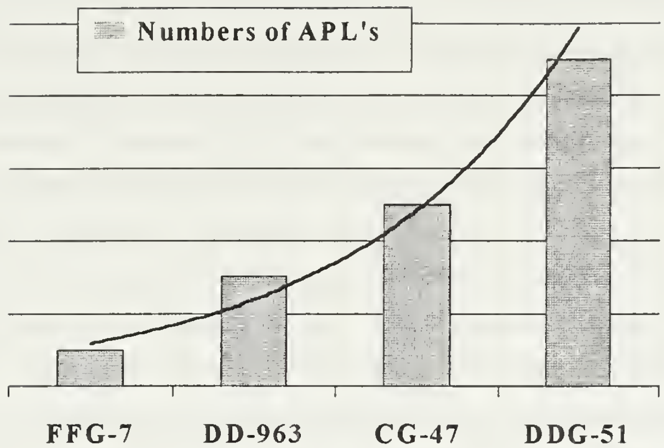

Figure 31 Trends for Applicable Parts Lists (APL's) for Surface Combatant Designs[112]

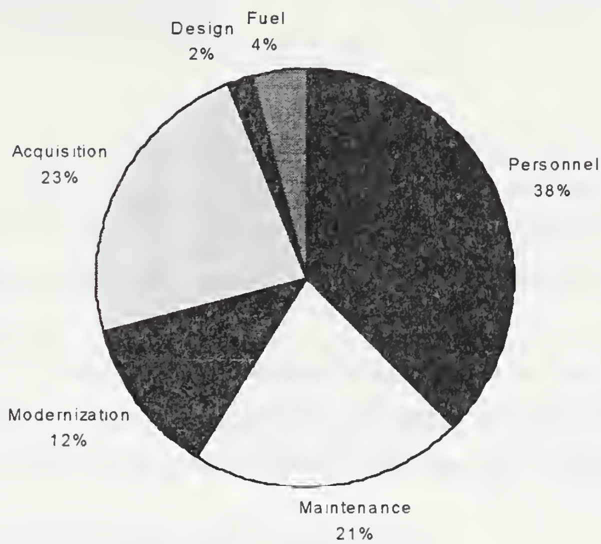

Figure 32 Life Cycle Cost Components for Typical Naval Ships[113]

4.5.2 Design Integration and Specifications

Design integration and specifications are the means by which the design achieves system definition and seeks to maintain designed performance in subsequent iterations. In the early stages of design, systems engineering decisions are meant to define the overall ability of concepts to satisfy expectations for total system effectiveness. As specific ship components (hull, prime movers, combat system elements) are considered in the design, these elements must be optimized relative to one another and relative to mission requirements. As design iterations are generated, there may be the tendency of component engineers to continuously change in response to changing input

[112] Todd Cary, Naval Sea Systems Command, interview on August 27, 1997, Arlington, VA.
[113] Ryan and Jons, "Improving the Ship Design, Acquisition and Construction Process", Association of Scientists and Engineers, 28th Annual Technical Symposium, 11 April 1991, page 13.

information from other component elements. Without mechanisms to manage these changes, it is likely that the design would diverge. This is the role of systems integration. Through the use of margins (see Chapter 1.1.3) and configuration control, design managers restrict the degree of change permitted over time. Configuration control (managed by means of a baseline 3-D product model, equipment lists, performance specifications, military specification, issuing arrangement drawings, etc) provides a design baseline that "freezes" those aspects of the design viewed as satisfactory with respect to the requirements.

In later design stages, design integration matures beyond configuration specification to component specification. Earlier discussions (see Chapters 3.3.1 and 4.4) demonstrate the changing roles of contract specifications in the design process. However, the selection of components and their exclusion from further design change must take place in the design process, whether dictated by the government during contract design or by industry in functional design. Ultimately, the design must be specified in order to allow production.

Task Element	Concept	Preliminary	Contract	Detailed			
				Functional	Transition	Zonal	Production
Systems Engineering, Design Integration & Configuration Control	1	1	1	1	1	1	1
Ship & Purchase Specifications, GFE/GFI & CDRLs		1	1	1	1	1	1
Specification Design History Input		1	1	1	1	1	1
GFE/GFI/VFI Specification			1	1	1	1	1
Design Control					1	1	1

Table 18 Design Integration and Specification Tasks

Table 18 provides a listing of the specific design tasks associated with design integration and specification. Note that these task effort profiles (Chapter 8.5) would likely change for a current design program to reflect a changing government to industry design transition point (see Figure 5). However the task elements (with perhaps different names) would still remain.

The input requirements for design integration include those elements of the process that are specific to design definition (hull, structures, marine systems, combat systems.) The design integration tasking receives the inputs of current design parameters and outputs constraints to the program manager for implementation.

4.5.3 Producibility and Production Engineering

Producibility and production engineering is the consideration of industrial capabilities relative to ship design and construction. This requires both the assessment of industrial capabilities relative to technologies incorporated in the design and inclusion of "design for production" elements in the design. To the first requirements, the industrial base necessary to support naval ship design and construction must be assessed. For instance, there only a few shipbuilders with facilities, knowledge and skills available to produce specialized hullforms (such as submarines) or to test advanced combat systems (such as the Aegis Weapons System.) The selection of specific ship design options (such as materials, size, weapon systems, etc) will naturally reduce the field of potential builders. The introduction of new technologies may further reduce the capable industrial base. It is a necessary task of design managers to understand the impacts of technology and design on the shipbuilders. Secondly, design for production must be included to achieve the cost goals described in Chapter 1.1.3. Specifically, the design must:

1. Develop a build strategy and product work breakdown structure.

2. Assess the design against the production process
3. Incorporate appropriate producibility enhancements.

It is apparent that this process of design for production is itself a closed loop system that seeks to optimize cost and production effectiveness relative to military effectiveness.

It is noted that design for production considerations were not adequately included in past designs. Due to requirements for competition, US yards have not been able to incorporate producibility to the extent necessary to realize savings. Consider Table 19. In foreign yards, designs are specifically tailored to the capabilities of the yards and their workers. As such, even in countries where workers are paid more, the labor required to produce a ship and the total labor costs are less. Consider the design task elements for the DDG-51, and hence the baseline naval ship design process model, shown in Table 20. The ship work breakdown structure was not formalized until late in the process. Again demonstrating the lack of producibility consideration in the final design.

Productivity	Japan	Korea	Germany	US
Employee-Days/Ship	45,000	99,000	65,000	100,000
Hourly Compensation (1990 US Dollars)	16.0	7.8	26.5	15.6
Total Labor Charges ($ million)	5.76	6.17	13.78	12.48

Table 19 Shipyard Productivity Comparison for Comparable Ship Designs[114]

There are significant efforts to change this trend and to incorporate producibility much earlier in the design process. For instance, the LPD-17 hullform design was enhanced with large flat plate construction, single curvature midbody and an elliptical bulbous bow (no fillet).[115] These enhances are a step in the direction of enhancing producibility. Current programs will further improve producibility by incorporating shipbuilders at the earliest stages of design.

To maximize the leverage of producibility on cost, a ship design must be optimized from the concept phase onward not only for mission needs and operational cost, but also for production schedule and construction cost. Producibility tasking may take several forms, but two are generally observed. First, producibility is assessed relative to fabrication, arrangements and materials. For those designs that are optimized for a particular shipyard's capabilities, ship arrangements (outfitting, block sizes, etc) and materials and fabrication (common material catalogue, limiting complex shape geometry) enhance productivity for the shipbuilder. Improved productivity means lower costs, better quality and shorter production schedules.

Task Element	Concept	Preliminary	Contract	Detailed			
				Functional	Transition	Zonal	Production
Industrial Facilities Design and Industrial Base Assessment (BASE)	1	1	1	1	1	1	1
Producibility, Fabrication & Materials Assessment		1	1	1	1	1	1
Ship Work Breakdown Structure				1	1	1	1

Table 20 Producibility and Production Engineering

114 Rost and Tighe, 1992 Shipyard Costs and Capabilities, Center for Naval Analysis, Alexandria, VA.

115 Fireman, Fowler, McIntire and Wilkins, "LPD 17: In the Midst of Reform", Naval Engineers Journal, May 1995, page 275.

However, competitive requirements of contracts necessarily limit the level of producibility optimization that can occur. For this reason, a second method of producibility assessment has been developed: Generic Work Breakdown Structure (GWBS). As its name implies, the method provides a generic method of assessing producibility. The method is centered around group technology construction and organization of design elements into families of structures and components.[116] For early design (pre-contract award) the method provides a tool to assess production impacts of design decisions and to minimize costs where possible.

For the design model, Table 20 provides the baseline progression of design tasks. Again, current design programs will see variations in the timing of design tasks and growth in the levels of producibility tasks. Dynamically, producibility incorporates specific ship characteristics (hull geometry, structural design, arrangements, machinery and payload components) to assess construction impacts. The output of producibility is assessed at the management level. Additionally, producibility is a key input factor to cost assessment.

4.5.4 Performance Assessment and Requirements Comparison

Performance assessment includes modeling design characteristics as a total system, calculating ship's performance based on total ship design parameters, and assessing the mission effectiveness relative to requirements. Performance assessment has improved in recent years through improvements in computer modeling capabilities. Specifically, Survivability and Vulnerability Modeling (SVM), Electromagnetic Workstation (EMW) models, Leading Edge Advanced Prototyping for Ships (LEAPS), and others provide increasingly robust environments to test system performance and effectiveness.[117] These models are the initial steps of a trend towards simulation based design (SBD.) Although, most levels of performance assessment still require physical modeling (such as hullform testing in towing tanks), improved computer modeling will eventually provide the means to test all performance requirements in the virtual environment.

Task Element	Concept	Preliminary	Contract	Detailed			
				Functional	Transition	Zonal	Production
Survivability & Vulnerability Assessment	1	1	1	1	1	1	1
Concept Performance	1	1	1	1	1	1	1
Damage Control System Design	1	1	1	1	1	1	1
NBC (CBR) Defense	1	1	1	1	1	1	1
Combat System Performance Assessment		1	1	1	1	1	1

Table 21 Performance Assessment and Requirements Comparison Tasks

Table 21 shows a progression of performance tasking that was performed for the DDG-51 program. The DD-21 program will include mission effectiveness assessment and task efforts such as: Extended Air Defense Simulation Model (EADSIM), Surface AAW Multi-Ship Simulation (SAMS), Naval Air Battle Engagement Model (NABEM II), Radar Analysis Model (RAM), ASW Programs Surface Ship Engagement Model (APSURF), and Generic Sonar Model (GSM).[118]

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[116] Storch, Hammon, Bunch and Moore, Ship Production, Society of Naval Architects and Marine Engineers, Jersey City, NJ, 1995, page 60.
[117] Myles Hurwitz, "Leading Edge Advanced Prototyping for Ships (LEAPS): an Integrated Architecture for Early Stage Ship Concept Assessment Software", David Taylor Research Center, Bethesda, MD, 1997.
[118] DD-21 Program Website, http://www.navsea.navy.mil.

Like other systems engineering disciplines, performance assessment requires input from all design definition disciplines. However, the output of assessment is often provided directly to designers. This is particularly true in the real-time design and selection of specific design characteristics such as arrangements, hull and deckhouse configuration and topside arrangement of combat systems.

4.5.5 Manning

Manning assessment and definition is the final discipline of systems engineering. Manpower studies begin with comparative estimates of ship functions to similar ship designs. Later studies provide detailed manning studies based on functional breakdowns of manning requirements. As manning levels are established for specific ship watch stations, human engineering are conducted to optimize human performance relative to mission performance.

For many years, manning was viewed as a non-constraining attribute. Namely, shipboard manpower was viewed as unlimited. Damage control, condition I watch stations and maintenance requirements often drove manning levels well above those levels required for daily operations. However, the fiscal need for reduced operational costs and the political desire to limit human exposure to threat environments now results in imposed manning levels. If this trend continues, manning assessment becomes increasingly important to both system and component design.

Task Element	Concept	Preliminary	Contract	Detailed			
				Functional	Transition	Zonal	Production
Manpower Estimate	1	1	1	1	1	1	1
Manning Study	1	1	1	1	1	1	1
Ship Manning Document		1	1	1	1	1	1
Human Systems (Factors) Engineering		1	1	1	1	1	1

Table 22 Manning Assessment Tasks

Table 22 shows the progression of manning tasks. These tasks require input primarily of those ship characteristics that impact human engineering and manning requirements including: ship arrangements and sizing, machinery systems and combat systems. Early output from manning impacts sizing of the hull, payloads and auxiliary systems. Later output provides specific requirements for accommodations (arrangements), machinery system modifications for human support and second order changes (changing maintenance requirements or selection of new equipment items) through program management.

4.6 Hull Engineering

The hull engineering node is itself a significant systems engineering effort. Naval architects, the primary participants in hull engineering, often claim the title of the "world's first systems engineers."[119] Specifically, hull engineering must balance weight, buoyancy, area, power and resistance while maintaining adequate static and dynamic stability and strength, both in intact and damaged conditions. Specific design spirals are developed to balance these characteristics. For instance, the MIT Math Model – FFX[120], balances hull characteristics, deckhouse

[119] Tibbitts and Keane, "Naval Ship Design in the 21st Century", Society of Naval Architects and Marine Engineers, Jersey City, NJ, 1993.
[120] Brown and Welsh, MIT Math Model – FFX, Massachusetts Institute of Technology course 13.412, fall 1996.

volume and power for fixed inputs of marine systems, combat payloads, mission requirements, and manning. The original design spiral developed by Prof. Evans performed a similar optimization for commercial ship designs. A specific examination of equations and physical relationships for hull design and engineering are beyond the scope of this work. Rather, the nature of the component design disciplines and their purposes relative to the design process are discussed.

It is important to note a general change in hull engineering disciplines over the past decades. In the past, arrangements and hull geometry and powering were often separate exercises from hydrostatic and hydrodynamic analysis. Although it was possible that the same individual or group of individuals might perform the design and analysis tasks, the considerable manual effort required to perform those tasks would necessarily cause them to be performed independently. This fact is apparent in IDEF charts and design spirals depicting very linear and distinct nodes. For instance, Prof. Evans design spiral generates a basic ship design from[121]:

1. Proportions and Powering Estimates
2. Lines and Body Plans
3. Hydrostatics and Bonjeans
4. Floodable Length and Freeboard
5. Arrangements
6. Structures
7. Powering Light Ship Weight Estimates
8. Capacities, Trim and Intact Stability
9. Damaged Stability
10. Comparisons to Cost and Owners Requirements
11. Next Iteration…

This indicates an algorithm by which design disciplines are separated or design tasks are linear. However, today's design tools are allowing seamless design and analysis with real-time iteration and feedback. For instance, hull geometry software often includes modules to create hullforms, assess resistance, generate hydrostatic properties, assess maneuverability and determine seakeeping. These integrated packages allow a single designer to immediately see the impact of a hull geometry change on resistance or buoyancy. Inclusion of internal properties (hull subdivision, weight distributions and tank placements) allow a designer to perform major arrangements and assess those choices for stability. Obviously, the advantage of the integrated environment is fewer design errors, reduced communication overhead, and greater productivity.

Based on the DDG-51 program data, some integrated design and analysis was available in concept design. However, this was less apparent in preliminary design and beyond. As such, the current model considers the efforts of hull engineering as separate disciplines. Future variations of the design process model, may reflect the integrated environment through a merging of design disciplines. However, design tasking will not entirely merge as detailed design tasks (such as structural engineering and arrangements) are still specialized disciplines requiring separate

[121] J. Evans, "Basic Design Concepts", Naval Engineers Journal, November 1959.

design actions. For instance, Newport News Shipbuilding uses an integrated software environment (VIVID system using a 3D product model) in detailed design.[122] Although the system provides a common interface and model information is fully accessible to all designers, the design team still requires separate structural designers, weight engineers, arrangement specialists, etc… to perform specific design tasks, and discuss design and analysis results in a team environment.

The task and productivity hull design levels for the baseline case (DDG-51 program) are provided in Chapter 8.5. The justification for the DSM is provided below.

4.6.1 Hull Geometry

Hull geometry is the cornerstone of hull engineering. Hull geometry, or the ship's lines, must meet "precise and unambiguous" design constraints…and will "consist of orthographic projections of the intersections of the hull form with three mutually perpendicular sets of planes."[123] As simple as that may sound, the process is quite complex. The selection of specific hull parameters (length, beam, draft), hull coefficients (prismatic, waterplane, block, midship section), and fairing of hull lines requires iteration and trade-off. To facilitate early design, parametrics and established design lanes are often utilized to estimate hull size and shape.[124] These parameters typically require estimates of weights, weight distribution and desired hull speed as inputs. The parameters are then iterated for convergence against requirements. More advanced hull geometry algorithms, such as the HULGEN program in ASSET, combine parametric selections for baseline sizing with a parent hull design to fair intermediate station values to the hull parameters and coefficients. These methods provide a consistent basis for concept trade-off and perturbations. However, critics point out that use of design lanes constrain innovation.

At the preliminary design stage, hull geometry uses 3-D graphical modeling and scale model construction. As with performance assessment (Chapter 4.5.4), hull geometry design matured greatly with the introduction of modeling programs like Hull Form Definition System (HFDS) with its integrated generation and manipulation modules (FastShip, FASTGEN, and I/VDS.)[125] These programs provide increased ability to both generate and optimize hull forms relative to resistance, particularly for monohull designs. Other hull performance analysis, like seakeeping and stability, is also facilitated by common, digital, hull geometry definitions. Unusual hullforms, such as multi-hull designs or the wave piercing bow, must still be physically modeled and tested. Such testing not only supports the current design, but provides calibrating data for future computer modeling.

In addition to the basic hull geometry, other hull characteristics may be selected and modeled to enhance performance. For instance, bow (like the bulbous bow) and stern configurations are optimized to reduce resistance while maintaining adequate seakeeping characteristics.

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[122] Scott Ripley, Interview at Newport News Shipbuilding, Newport, VA, August 29, 1997.
[123] Normal Hamlin, "Ship Geometry", Principles of Naval Architecture, Society of Naval Architects and Marine Engineers, Jersey City, NJ, 1988, Volume I page 1.
[124] Gale and Scott, "Early Stage Ship Design Seminar", Society of Naval Architects and Marine Engineers, Jersey City, NJ, 1988.
[125] Whatmore and Wintersteen, A Review of Extant Design Tool Capabilities to Identify Common Design Tools for Future Collaboration, Naval Surface Warfare Center Carderock Division, Bethesda, MD, 1997, page 20.

Task Element	Concept	Preliminary	Contract	Detailed			
				Functional	Transition	Zonal	Production
Principle Dimensions	1	1	1	1	1	1	1
Parent Ship Properties	1	1	1	1	1	1	1
Hullform	1	1	1	1	1	1	1
Lines Drawings	1	1	1	1	1	1	1
3-D Model		1	1	1	1	1	1
Curves of Form		1	1	1	1	1	1
Hull Design Specifications Input		1	1	1	1	1	1
Hull Design History Input		1	1	1	1	1	1
Model Test Plan and Model Construction Plan		1	1	1	1	1	1
Stern Reconfiguration			1	1	1	1	1

Table 23 Hull Geometry Tasks

Table 23 shows the progression of hull geometry tasks in the design process. As discussed above, initial tasks are parametrically generated. The inputs includes weights, mechanical and combat systems, and requirements (speed, resistance, stability). Hull geometry represents a field of pure design. In other words, hull geometry is the definition of ship characteristics without explicit performance analysis (hull performance analysis is addressed as separate disciplines.)

Generally, all disciplines may be categorized as pure design, pure analysis (a discipline that describes the performance of a design characteristic, but does not necessarily have the capability or authority to modify that characteristic) or some combination of design and analysis. As a pure design discipline, hull geometry must provide hull engineering input to analysis disciplines which include: weight engineering, hydrodynamics, structures, marine engineering, cost and programmatics.

4.6.2 Weight Engineering

Weight engineering is a discipline of assessment and design. Weight engineering estimates distribute and account for mass distributions in the ship. In early design iterations, these distributions may be purely empirical with only a few mass locations (such as engines or combat systems) explicitly known. As the design matures, weight engineering relies increasingly on known arrangements, structural specifications, machinery integration and combat systems integration for specific placement of weights and their locations. These tasks are considered weight accounting. Another task is hydrostatic definition of the hull. Using the defined hull geometry and internal subdivision (arrangements), weight engineers generate bonjean curves, floodable length curves, and other hydrostatic displacement tools. Given mass-moment and hydrostatic properties, static stability (stability for specific angles of heel) is assessed. The analysis will include both intact and damaged conditions.

Task Element	Concept	Preliminary	Contract	Detailed			
				Functional	Transition	Zonal	Production
Deck Height Reduction Study	1	1	1	1	1	1	1
Machinery Space Tightness Study	1	1	1	1	1	1	1
Tank Arrangements	1	1	1	1	1	1	1
Bonjean Curves	1	1	1	1	1	1	1
Stability Assessment	1	1	1	1	1	1	1
Weight & Mass Properties Analysis	1	1	1	1	1	1	1
Stability Specifiation Input		1	1	1	1	1	1
Stability Design History Input		1	1	1	1	1	1
Weight (3-, 5-Digit & Contract Weights/Centers) Estimates		1	1	1	1	1	1
Contract Design Weight Estimates		1	1	1	1	1	1
Weight Control Program Reports		1	1	1	1	1	1
Weight Specifications Input		1	1	1	1	1	1
Weight Design History Inputs		1	1	1	1	1	1
Construction Margin Report		1	1	1	1	1	1
Weight Database (to initialize design)		1	1	1	1	1	1
Margin Allocations		1	1	1	1	1	1
Floadable Length		1	1	1	1	1	1
Intact and Damaged Stability Analysis		1	1	1	1	1	1
Volume and Displacement		1	1	1	1	1	1
Master Weight Files and Data Sheets			1	1	1	1	1

Table 24 Weight Engineering Tasks

Table 24 shows the progression of weight engineering tasks. These tasks are dominated by accounting and analysis. As such, weight engineering requires input from all design specific disciplines as well as requirements. Output goes to hydrodynamics (seakeeping requires righting moment data) and provides first order analysis to structures (for weight distribution curves), arrangements, and systems selections (i.e. weight critical loads may need to be moved or reduced.)

4.6.3 Hydrodynamics-Resistance and Powering

Resistance and powering analyzes the link between requirements, hull geometry, appendage design, and propulsion plant selection. For early design, resistance is empirically based (Taylor Standard Series resistance.) Later design analysis includes model testing and numerical methods (computational fluid dynamics (CFD) models.) As discussed previously (see Chapter 4.6.2), the analysis methods for hydrodynamics are increasingly integrated with design tools to provide improved design iteration.

Task Element	Concept	Preliminary	Contract	Detailed			
				Functional	Transition	Zonal	Production
Powering/Resistance Charactisterics	1	1	1	1	1	1	1
Speed-Power Requirements and Report	1	1	1	1	1	1	1

Table 25 Hydrodynamics-Resistance and Powering Tasks

Table 25 shows the two primary resistance analysis task types (resistance determination and report of results relative to requirements.) Input requirements include all factors effecting resistance and speed calculations (hullform, appendages, powering.) For the current naval ship design process model, output includes hull geometry, requirements, appendage design and propulsion plant design. Future model considerations merge many of the design and analysis tasks in an integrated design environment.

4.6.4 Hydrodynamics-Seakeeping

Seakeeping is the measure of mission performance of the hullform, and, subsequently, all ship systems, which considers ship motion in the operational environment. Like resistance, it represents a pure analysis discipline

that is being increasingly integrated in a design environment. For instance, the current generation of HFDS provides both geometry manipulation and seakeeping analysis with programs including: Ship's Motion Program (SMP), SWMP and SWISP modules for SWATH hullforms, and Seakeeping Evaluation Program (SEP). In past programs, seakeeping was rarely addressed in early design. This fact is apparent in the tasking from Table 26. However, seakeeping is increasingly important in early design today due to demanding mission requirements. These requirements include a greater range of operating environments and greater seakeeping demands to support flight operations, crew and payload performance.

Task Element	Concept	Preliminary	Contract	Detailed			
				Functional	Transition	Zonal	Production
Seaway Seakeeping Performance Assessment	1	1	1	1	1	1	1
Seakeeping Report			1	1	1	1	1

Table 26 Hydrodynamics-Seakeeping Tasks

Seakeeping requires inputs from requirements, hullform, appendages and weight properties, as well as auxiliary systems (active stabilization). Outputs from seakeeping go to programmatics, hull geometry and appendage sizing. A very important output is provided to structural analysis. Structural analysis uses dynamic sea loads to develop the structural design for the hull.

4.6.5 Hydrodynamics-Maneuvering, Control and Appendages

Maneuvering, control and appendages are the remaining system considerations relating to the hull-water interface. "(Maneuvering) includes starting, steering a steady course, turning, slowing, stopping, backing…"[126] These tasks include the design and assessment of appendages including rudders, propellers, and passive stabilizers. Specific tasks are shown in Table 27 below. These tasks are determined in a manner similar to all previous design disciplines. Additionally, the tasks are supplemented by the an excellent summary and description of the component tasks found in Table 22 of Principles of Naval Architecture.[127]

Task Element	Concept	Preliminary	Contract	Detailed			
				Functional	Transition	Zonal	Production
Propeller Design Report and Diagrams	1	1	1	1	1	1	1
Controllability Assessment	1	1	1	1	1	1	1
Propeller Trade-Off Study		1	1	1	1	1	1
Propeller Specification Input		1	1	1	1	1	1
Propeller Design History Input		1	1	1	1	1	1
Control and Manuevering System Design		1	1	1	1	1	1
Hull Equipment & Appendage Design		1	1	1	1	1	1
Maneuvering and Propeller Specification Inputs		1	1	1	1	1	1
Maneuvering and Propeller Design History Inputs		1	1	1	1	1	1
Hydro Performance Assessment		1	1	1	1	1	1
Steering Gear		1	1	1	1	1	1

Table 27 Hydrodynamics-Maneuvering, Control and Appendages Tasks

Data interfaces for maneuvering and control include inputs from requirements, hullform, weight distributions (for turning moments), propulsion plant configuration (for propeller sizing) and auxiliary systems (for active control systems.) Output goes to programmatics and performance, producibility (for integration of appendages), hull

[126] Crane, Eda, Landsburg, "Controllability", Principles of Naval Architecture, Society of Naval Architects and Marine Engineers, Jersey City, NJ, 1988, chapter IX.
[127] Ibid.

geometry and weights (for design to performance iterations) and mechanical systems (for adequate sizing of maneuvering auxiliaries.)

Note that propeller design is included with maneuvering design. It is equally acceptable to include those tasks under propulsion engineering.

4.6.6 Structural Engineering

Structural engineering requires the design of hull and deckhouse structure to resist static and dynamic loads on the hull. Additionally, structural engineering provides for support and isolation of installed equipment by means of foundations and force absorbers. Structural engineering requires inputs from mission requirements and assessed performance, hull configuration and loading, and installed equipment and systems. Structural engineering is a combined design and analysis discipline. Early structural design uses parametric weight distributions and historical wave characteristics, generates anticipated longitudinal bending stresses from these characteristics, and iterates this process to define a midship section. As the design matures, sections are generated for multiple locations in the hull. In areas of higher risk (such as dynamic loading of radars on masts), finite element analysis (FEA) may be used. Later in the process, critical spaces (machinery box, magazines, etc) and eventually the entire ship are modeled in FEA. During detailed design, structural engineering is a prime focus for hull design as the complete hull geometry is translated into structural components and details. Specific implementation of structural design is found in Hughes[128] and Paulling[129]. Structural output is used by programmatics and performance assessment, hull geometry and weights, and arrangements.

Task Element	Concept	Preliminary	Contract	Detailed			
				Functional	Transition	Zonal	Production
Define Midship Section Structure	1	1	1	1	1	1	1
Longitudinal Strength Assessment	1	1	1	1	1	1	1
Payload Structural Assessment	1	1	1	1	1	1	1
Shipyard Producibility Practices	1	1	1	1	1	1	1
Frame Spacing	1	1	1	1	1	1	1
Structural Assessment	1	1	1	1	1	1	1
Noise & Vibration Analysis	1	1	1	1	1	1	1
Design Criteria		1	1	1	1	1	1
Structural Specfication Input		1	1	1	1	1	1
Calculation Report		1	1	1	1	1	1
Structural Arrangement		1	1	1	1	1	1
Deck Structural Drawings		1	1	1	1	1	1
Structural (Scantling) Drawings		1	1	1	1	1	1
Superstructure/Deckhouse Structural Drawings		1	1	1	1	1	1
Foundation Design & Weight Effective Foundations		1	1	1	1	1	1
Structural Design History Input			1	1	1	1	1
Bulkhead Structural Drawings			1	1	1	1	1
PSDM			1	1	1	1	1

Table 28 Structural Engineering Tasks

Table 28 shows the progression of structural design tasks. Note from Chapter 8.5 that over the course of the process structural productivity must increase dramatically (by a factor of 200%) to accommodate the substantial increase in structural design effort required for detailed design.

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[128] Hughes, Ship Structural Design, Society of Naval Architects and Marine Engineers, Jersey City, NJ, 1988.
[129] Paulling, "Strength of Ships", Principles of Naval Architecture, Society of Naval Architects and Marine Engineers, Jersey City, NJ, 1988, chapter IV.

4.6.7 Space and Arrangements

Space and arrangements are the means by which the hull volume is allocated and optimized. In pre-detailed design, general arrangements identify the location, physical boundaries and function of each space in the ship. These locations are utilized for weight engineering, survivability assessment (redundancy, separation and permeability), and manning accommodations. In detailed design, the concern is the development of arrangements of equipment within each space with provision for required access to every component on the ship. Specifically, the location of equipment must be selected to satisfy individual component performance (location of radar transmitters to minimize wave guide runs), component system performance (redundant fire pumps separated for survivability) and total system performance (zonal distribution and Collective Protective System (CPS) location.)

The outputs from arrangements are a significant input to programmatics and specifications. In particular, arrangement drawings and Master Equipment Lists (MEL) are an important component of configuration baseline designs that complete a design iteration. As a design element, arrangements are utilized by performance assessment and weights for analysis. Additionally, hull arrangements must converge with machinery and combat systems arrangements. (Note that machinery systems and combat systems integration include specific arrangement tasks due to the unique requirements of those disciplines.)

Table 29 shows the progression of space and arrangements design tasks. Note that like most other hull engineering disciplines, initial tasks are based on parametric or empirical design, and later phases rely on physical placement of components.

Task Element	Concept	Preliminary	Contract	Detailed			
				Functional	Transition	Zonal	Production
Arrangements	1	1	1	1	1	1	1
Compartment & Access (C&A) List & Oufit Drawings	1	1	1	1	1	1	1
Area Requirements	1	1	1	1	1	1	1
Volume Requirments	1	1	1	1	1	1	1
HVAC, CPS and Zonal System Arrangements	1	1	1	1	1	1	1
Specification Control Drawings (SCD) and Specification Inputs		1	1	1	1	1	1
2D/3D CAD Model Extraction		1	1	1	1	1	1
Outfitting Trade-Off Studies		1	1	1	1	1	1
Office Space Arrangement Drawigns		1	1	1	1	1	1
Medical Arrangements Drawings		1	1	1	1	1	1
Outfitting Specifications Inputs		1	1	1	1	1	1
Outfitting Design History Inputs		1	1	1	1	1	1
General Arrangement Drawings		1	1	1	1	1	1
Habitability Drawings		1	1	1	1	1	1
CPS/Zonal Distribution System Drawings		1	1	1	1	1	1
Design History Input		1	1	1	1	1	1
Functioinal Drawings - Series "K"				1	1	1	1
Fabrication Drawings - Series "F"						1	1
Installation Drawings - Series "I"						1	1
Closure List						1	1

Table 29 Space and Arrangements Tasks

4.7 Machinery Systems Engineering

Machinery systems engineering, or marine engineering, is the selection and integration of propulsion, electrical and support systems. Historically, the boundary between machinery engineering and hull engineering is indistinct. For instance, propeller design is equally important to both disciplines. Likewise, the hull form determines the propulsion power required to achieve sustained speed levels and the selected propulsion plant

determines the necessary hull form to support the plant. These interdependencies are reflected in the DSM for naval ship design. Detailed examples of machinery tasks and interdependencies can be found in Harrington[130].

Machinery engineering is an interdisciplinary task set that draws on engineering disciplines ranging from mechanical to electrical to chemical to civil engineering. Specific components of machinery design include:

- Propulsion and transmission systems
- Electrical generation and distribution
- Environmental, fluid and support auxiliary systems
- Non-combat related auxiliary systems (deck, handling and aviation machinery)

In addition to component selection and design, the machinery plant must be integrated into the total ship and consider the total impact of machinery systems on fuel capacity, stack length, and net component accounting (weight, space and specification). Machinery system discipline productivity and task levels are provided in Chapter 8.5.

4.7.1 Machinery Systems Design and Integration

Machinery system design is the integration of subordinate mechanical systems in the ship design. For early design phases, this integration provides determination of total fuel requirements (endurance fuel and electrical generation fuel) and machinery arrangements. Preliminary machinery stack length and plant sizing is parametrically linked to ship dimensions (length, beam, hull depth). As such, ship geometry is a key input to system design. Additional inputs include requirements, performance assessment, weights and arrangements (hull and topside), hull performance (resistance), and cost. In later design stages, machinery systems become better defined with specific components selected via designation in the Master Equipment List (MEL) and other parts lists. System diagrams (cableways, piping, etc) are developed and refined in coordination with general arrangements. Machinery control systems are developed for the selected mechanical systems.

The output from systems design must match general and topside arrangements, weight accounts, performance estimates and programmatic requirements. Table 30 lists the progression of system tasks. Note that throughout mechanical systems design, there is little mention of mechanical systems development. Rather, it is assumed that the chosen systems are mature and available when required for design integration. Future iterations of the design model may consider specific development schedules for high risk technologies (such as RACER for DDG-51 or Integrated Propulsion System (IPS) for DD-21) and represent those dynamics endogenously.

[130] Roy Harrington, Marine Engineering, Society of Naval Architects and Marine Engineers, Jersey City, NJ, 1992.

Task Element	Concept	Preliminary	Contract	Detailed			
				Functional	Transition	Zonal	Production
Fuel Requirements	1	1	1	1	1	1	1
Ship System Development	1	1	1	1	1	1	1
Machinery Arrangement	1	1	1	1	1	1	1
Master Equipment List (MEL)		1	1	1	1	1	1
SSES & LBEF & SSEB Support		1	1	1	1	1	1
Machinery Developments Studies		1	1	1	1	1	1
Machinery Controls		1	1	1	1	1	1
Machinery Control Arrangements		1	1	1	1	1	1
Outfit and Furshining			1	1	1	1	1
Material Design Standards				1	1	1	1
System Diagrams with associated parts list				1	1	1	1
Interference Checking					1	1	1

Table 30 Machinery Systems Design and Integration

4.7.2 Propulsion Systems

Propulsion systems engineering is the selection and design of the components of the propulsion train. As discussed previously, these efforts do not require the specific development of a propulsion engine (such as a specific gas turbine or diesel engine). Rather, they provide for the selection of engines, determination of required ship support for the engines and development of power train elements for transmission of power. It is possible that selected engine systems may not be mature during the initial design phases. This is particularly true during the development of nuclear power systems or new technologies (such as IPS.) For the purposes of the current model, these issues are ignored. However, such issues can have a significant cycle time impact on design. Aside from prime movers, many unique components such as reduction gear, shafting and clutches, may be specifically designed within the context of the naval engineering process. Table 31 describes many of the specific power system decisions that must be made during this tasking.

Number of propulsors/shafts	Direction of shaft rotation	Number of engine rooms
Number/Type of prime movers	Gear Type/Location	Exhaust energy usage
Power transmission method	Fuel Type	Power plant location/geometry
Power plant mounting	K factors	Gear Configurations
Regeneration	Thrust reversing method	Control type
Inlet type	Exhaust type	Deicing method
Power plant locations	Airborne noise control	Vibration control

Table 31 Key Propulsion System Trade-Off Parameters[131]

In concept design, propulsion plant engineering is typically restricted to selection of a powering concept and determination of adequacy of the concept to meet performance requirements. As such, inputs must include performance, hull resistance, propulsor concepts, hull arrangements and propulsion support systems. Note that propulsor design is included with maneuvering and control. It would be equally acceptable to include propulsor design with the propulsion train instead.

[131] Myron Ricketts, Manual for Naval Surface Ship Design Technical Practices, Naval Sea Systems Command, Washington DC, 1980.

As machinery space, weight requirements, and fuel needs are generated, the output is iterated against performance, maintenance and manning concepts, weights and hull arrangements, support systems and cost. Later iterations of the propulsion plant further refines these outputs and examines transmission concepts, vibration, stack design, and fluid systems. Final design stages require specific arrangements of propulsion components and support systems and management of production preparations (parts and components ordering.) The complete progression of propulsion system tasking is found in Table 32.

Task Element	Concept	Preliminary	Contract	Detailed			
				Functional	Transition	Zonal	Production
Main Propulsion Concept	1	1	1	1	1	1	1
Main Engine Selection	1	1	1	1	1	1	1
Propulsion System Trade-Off Study		1	1	1	1	1	1
Fluid System Diagrams		1	1	1	1	1	1
Endurance Fuel Requirements		1	1	1	1	1	1
Propulsion System Design Report Input		1	1	1	1	1	1
Propulsion System Specification Input		1	1	1	1	1	1
Shafting Drawing		1	1	1	1	1	1
Shafting Vibration Analysis		1	1	1	1	1	1
Propulsion System Design History Input			1	1	1	1	1
Stack Gas Flow			1	1	1	1	1

Table 32 Propulsion Systems Tasks

4.7.3 Electrical Systems

Electrical systems design follows a similar progression as propulsion plant design. During early design stages, an electrical system concept is developed to accommodate performance requirements, support systems and combat systems. Electrical requirements are initially sized based on manpower levels, hull parameters and known power requirements for selected shipboard systems. Later design stages examine electrical load demand and distribution. Management and accounting of electrical capacity and demand becomes increasingly important later in design as system growth naturally occurs.

Electrical system growth is substantial over time. The first naval vessel equipped with electrical power (the cruiser USS TRENTON in 1883) had 13.2 kW of power capacity. In contrast, the DD 963 destroyer (1970's) has 6000 kW capacity and the DDG-51 (1980's) has 7500 kW. This growth in electric requirements is attributed to the following technological developments[132]:

- Weapons development including ammunition handling and electronic warfare systems
- Electronic command, control, and navigation systems with high powered radar, sonar, and electronic data processing equipment
- Habitability improvements including electric heating, air conditioning, illumination, and refrigerated storage
- Increased use of electric and electrohydraulic auxiliary systems

These trends require some increases in electrical design effort. However, the greatest trend impacting effort is the inclusion of Integrated Power Systems (IPS.) With the design of an "all-electric" ship, this category of design could experience significant growth.

For the current model, DDG-51 efforts are modeled with the task progression shown in Table 33.

[132] Ibid., page 10-8.

Task Element	Concept	Preliminary	Contract	Detailed			
				Functional	Transition	Zonal	Production
Electric Distribution Design	1	1	1	1	1	1	1
Electric Plant Concept	1	1	1	1	1	1	1
Electrical Line Diagram		1	1	1	1	1	1
Lighting Analysis		1	1	1	1	1	1
Electrical System Specification Input		1	1	1	1	1	1
Electrical System Trade-Off Study		1	1	1	1	1	1
Electrical Load Analysis		1	1	1	1	1	1
Electrical System Design History Input			1	1	1	1	1

Table 33 Electrical Systems Tasks

4.7.4 Auxiliary and Support Systems

Auxiliary systems design includes those system required to support ship systems. Specifically, SWBS group 500 items dominate this category of design. Auxiliary systems are selected based on inputs from requirements and performance, manning, hull geometry (utilized for concept level sizing), control systems, available weight and space, propulsion and electrical systems, and combat systems. The selected systems provide capabilities for:

- Damage Control…ventilation, dewatering, sensing, CPS
- Environmental Control…heating, ventilation, air conditioning, refrigeration
- Fluid Management…sea water supply, fresh water generation and distribution, air/gas supply
- Pollution Control…oily waste systems, sewage treatment, solid waste disposal, chemical/toxic waste disposal

As a closed loop design process, output selections are provided to input categories and costing for comparison and iteration. With the introduction of increased computing capacity aboard modern warships, this category may grow to provide adequate environmental conditioning. For the baseline case, tasking is established per Table 34.

Task Element	Concept	Preliminary	Contract	Detailed			
				Functional	Transition	Zonal	Production
Distributive System and Auxiliaries Design	1	1	1	1	1	1	1
Fluid System Trade-Off Studies		1	1	1	1	1	1
Fluid System Arrangement Diagrams		1	1	1	1	1	1
Fluid System Design History Input		1	1	1	1	1	1
Fluid System Specifications Input		1	1	1	1	1	1
HVAC Trade-Off Studies		1	1	1	1	1	1
HVAC Diagrams and Arrangement Drawings		1	1	1	1	1	1
Fan Room Arrnagements		1	1	1	1	1	1
HVAC Design History Input		1	1	1	1	1	1
HVAC System Report		1	1	1	1	1	1
HVAC Specification Input		1	1	1	1	1	1
HVAC System Requirements and Criteria			1	1	1	1	1
Steering Systems			1	1	1	1	1

Table 34 Auxiliary and Support Systems Tasks

4.7.5 Deck, Handling and Aviation Support Systems

The remaining systems are those components assigned to SWBS groups 570, 580 and 590. Specifically, these systems are required to support conventional ship operations (like mooring, anchoring, towing, etc), underway replenishment operations (UNREP) and aviation operations. These systems are less dependent on input then previous mechanical systems. Specifically, input is required from performance and requirements, weight and space allocations and electrical and support system budgets. The design output is returned to the input disciplines and

cost, manning and maintenance. The progression of task elements is provided in Table 35. For future design models, these tasks will input to topside design because of their importance of reducing ship signatures.

Task Element	Concept	Preliminary	Contract	Detailed			
				Functional	Transition	Zonal	Production
Deck/UNREP Systems	1	1	1	1	1	1	1
Deck System Trade-Off Studies		1	1	1	1	1	1
Anchor, Mooring & Towing Drawings		1	1	1	1	1	1
Deck Systems Design History Input		1	1	1	1	1	1
Deck Systems Specification Input		1	1	1	1	1	1
Aircraft Support System		1	1	1	1	1	1
Boat Handling and Stowage Arrangements and Drawings		1	1	1	1	1	1

Table 35 Deck, Handling and Aviation Support Systems Tasks

4.8 Mission Systems Engineering

Mission systems engineering, also known as combat systems engineering, is the selection and integration of those combat payloads necessary to meet the mission requirements of the surface combatant. The selected systems must be fully integrated into the arrangements of the combatant. Recall the combat systems trends discussed in Chapter 1.1.3 and Figure 12. Older combat systems (gun systems and visual guidance) were weight critical, dense, and placed low in the hull. The resulting ship had large displacement, but smaller beam for the desired stability requirements. The combat system provided a reaction time suitable for the threats of that time. As threat capabilities advanced, combat systems matured with the transition from guns to missiles and visual to radar guidance. Consequently, the ship integration issues changed. Modern warships must accommodate volume and height critical systems to achieve necessary performance. The result was initially lower displacement in ships like the DD-963 with less dense, moderately high systems. As response time and multi-mission performance demanded increased sensor height and greater payload volume, displacement and beam growth was necessary to provide adequate stability for highly placed radar systems.

Note that combat systems engineering in this context is not the design of combat systems themselves. The fields of combat systems design (detect to engage chains) and testing (probability of detect and kill, reliability, etc) represent product development processes unto themselves. Although these systems are becoming increasing integrated into the ship development process (such as the Aegis Weapon System and CG-47), removing weapon systems development from the boundaries of the model is necessary to allow examination of naval ship design. Future models may endogenously include major weapon systems development. However, these systems should only be included if the weapon systems development schedule are shown to dynamically influence the ship design process.

Baseline productivity and task levels for the DDG-51 program combat systems integration (independent of combat systems development) are provided in Chapter 8.5.

4.8.1 Mission Systems Selection, Design and Integration

Mission systems include those payloads required for the combatant to satisfy specific warfare requirements of the ORD. These systems can include communications (both internal and external), sensors, weapons and control. It

does not include the development process of those systems, but rather assumes systems are available and must be integrated with the ship design. Note that there has been tremendous criticism over the years concerning the apparent disconnect between the ship design community and weapon systems development community.[133] Specifically, lack of coordination between the two communities has lead to tremendous schedule fluctuations. Consider Figure 33. The figure shows the months required to launch each vessel in the class for the CG-47 Aegis Cruiser. Note that the class experienced 4 major combat system baseline changes over the course of the program. This can be correlated to the four oscillations in delivery schedule. This trend dominates actual hours of effort which reflect the expected learning curve. Thus, schedule delays from late GFE/GFI/GFM effectively negate the benefits of production efficiencies. This trend is changing in current programs like DD-21 and should be considered in future model designs.

Input requirements for mission systems design include performance and requirements, weight and space budgets, support system capacity and topside arrangement issues. Output is iterated with the same disciplines as well as structural design and cost. The complete progression of design tasks is shown in Table 36.

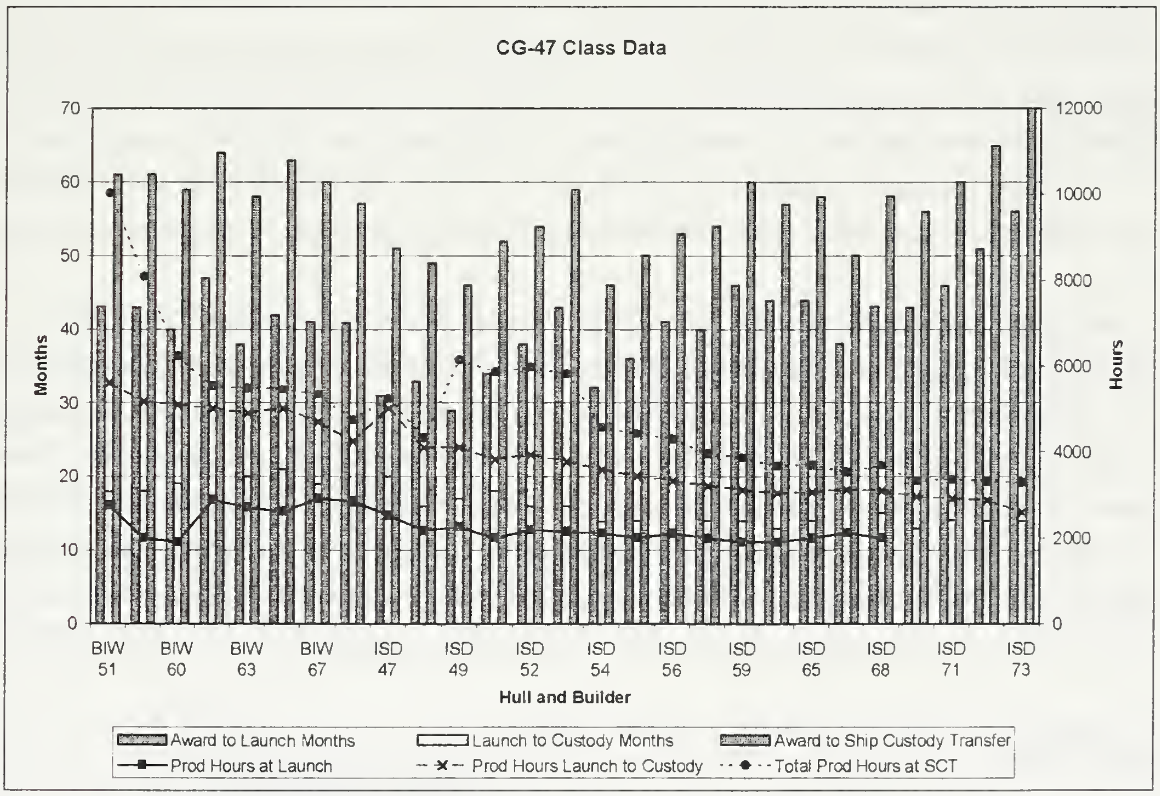

Figure 33 CG-47 Class Delivery Schedules and Production Efforts[134]

[133] Tibbitts and Keane, "Naval Ship Design in the 21st Century", Society of Naval Architects and Marine Engineers, Jersey City, NJ, 1993.

[134] Mike Jeffers, Interview at Naval Surface Warfare Center Carderock Division, Bethesda, MD, November 12, 1997.

Task Element	Concept	Preliminary	Contract	Detailed			
				Functional	Transition	Zonal	Production
Combat System Integration Management	1	1	1	1	1	1	1
IC/Navigation Integration and Diagrams	1	1	1	1	1	1	1
Exterior Comms (SPAWAR-NAVELEX) System & Antenna Integration	1	1	1	1	1	1	1
Shipboard Data Multiplex System (SDMS)		1	1	1	1	1	1
Combat Systems Design Support, Testing, IVCS & ISMS		1	1	1	1	1	1
Command and Control Space Arrangements		1	1	1	1	1	1
Mission Systems Design History Input		1	1	1	1	1	1
Mission Systems Specification Input		1	1	1	1	1	1
Armament and Weapon Systems Integration		1	1	1	1	1	1
IC Matrix			1	1	1	1	1

Table 36 Mission Systems Selection, Design and Integration Tasks

4.8.2 Topside Design and Integration

With the introduction of modern weapon systems (missiles, communications, and radars) has come increased need to manage topside design. Specifically, modern combat systems generate unique integration problems due to azimuthal coverage requirements, electromagnetic interference (EMI), signature reductions including radar cross section (RCS) and Infrared (IR), and aperture height requirements. These needs require detailed accounting and modeling of system interactions and allocation of valuable topside real estate. At the concept level, integration is typically limited to basic arrangement diagrams. The requirements for inputs include mission systems selected, distance and capacity of supporting systems, arrangements of non-combat system topside elements (deck, handling and aviation systems), and performance requirements. Of particular concern are the mass moment and subsequent stability of the ship. As topside systems demand increasing heights and weights, the impact on hydrostatic performance is significant. As discussed previously, these impacts are proving evolutionary in combatant ship design.

In later stages of topside design, specific analysis of EMI impacts, coverage, source-victim effects, and combat system performance must be addressed to optimize topside arrangements. Like hull engineering (HFDS), the demands of technology coupled with the current trend to integrate design and analysis has resulted in the creation of software suites for topside engineering. Systems such as LEAPS and Electromagnetic Engineering (EMENG) are providing topside engineers with the ability to analyze greater combat systems detail much earlier in the design process. Such efforts are necessary if modern warships are to meet current requirement demands for passive and active defense. Later variations of the design process model may be modified to reflect the increased concept design effort necessary for programs like the DD-21. The baseline tasking progression is shown in Table 37.

Task Element	Concept	Preliminary	Contract	Detailed			
				Functional	Transition	Zonal	Production
Topside and Combat Systems Integration	1	1	1	1	1	1	1
Topside & Combat Systems Arrangements	1	1	1	1	1	1	1
Topside Arrangement Drawings		1	1	1	1	1	1
EMI Analysis		1	1	1	1	1	1
Arcs of Fire & BAM Analysis		1	1	1	1	1	1

Table 37 Topside Design and Integration Tasks

Output from topside engineering is iterated with mission systems selection, support systems, arrangements, weight, performance, maintenance and manning, and programmatics.

4.9 Cost Engineering

A final component of the total systems engineering process, along with performance assessment and schedule, is cost. In this context, cost represents all aspects of total ownership cost (TOC) for the developing system. In the context of the naval ship design process, cost engineering represents that component of ship design by which the acquisition and life cycle cost of the developing design is assessed against program cost constraints. As such, it does not include the expenditures of funds for R&D or current spending on the design process (those current costs are modeled explicitly, see Chapter 5.5). Cost engineering addresses the specific cost dynamics discussed previously in Chapters 1.1.3 and 2.3. These behaviors demonstrate that cost is and will continue to be the primary driver in naval ship design and acquisition. DDG-51 cost constraints explicitly operated as a closed loop feedback control process…indicative of a dynamic control process.[135] Exceeding cost estimates resulted in significant design effort and design change (see Figure 16.) This trend is severely criticized in light of questionable cost estimate accuracy. The result is increased demand for robust costing methods such as Product-Oriented Design and Construction (PODAC) cost models and access to costing models such as ACEIT at the engineering level. These issues are beyond the scope of this work. However, the impacts of these methodologies provide more tasks in early design off-set by decreased iterations generated from cost. The result is a relatively constant productivity rate for costing and decreased feedback late in the design process (after concept design.)

Chapter 8.5 contains productivity and tasking baseline data for the DDG-51 program. Specific types of cost estimates and their relationships to the design process are provided below.

4.9.1 Cost Estimates and Analysis

Cost estimates and analysis are the aggregates of all engineering cost studies for the naval ship design process. These estimates represent specific types of cost estimates required by DoD doctrine at each milestone and, consequentially, each design phase. Note that design process budgeting considers a separate process within the naval ship design model. Budgeting for the design is accomplished by the Planning, Programming, and Budgeting System (PPBS) and is explicitly modeled (see Chapter 5.5).

Cost estimates are designated by classes, which correspond to a given phase of the design process.[136] The least detailed classes of cost estimates are Class E and F. They are based on 1-digit weight based cost models such as parametric cost estimating relationships (CERs). If specific costs for components (propulsion systems or combat systems) are known, they are included. The ACEIT model uses CERs. Class E and F estimates provide order of magnitude estimation for concept design. At the end of concept design, a Class D estimate may be provided. Class D estimates provide refined weight based cost and establish the basis for design-to-cost estimates for contracting. During preliminary design, Class C estimates are provided. Class C estimates are budget quality estimates, but are still based on weight based parametrics. However, these estimates increasingly incorporate engineering analysis of design characteristics. For instance, with the introduction of PODAC costing methods, Class C estimates should

[135] Hope and Stortz, "Warships and Cost Constraints", Naval Engineers Journal, March 1986, page 41-43.

begin to reflect direct producibility cost impacts beyond simple shaping functions which are often applied to parametrically based costs. Additionally, life cycle cost models are being developed to provide cost analysis of manning, ILS, and operational impacts as well as development and production. For example, the ACEIT cost model is modified to provide differentiation of varying production rates and multi-year contracts. Class B estimates are provided during contract design. These estimates establish the cost ceiling for the acquisition (again by design-to-cost methodology and, typically, weight based costing models) by which contract bids are judged. Class B estimates are often referred to as Bid Evaluation Cost Estimates. Detailed cost estimates, or post-budget costs, are realized costs associated with material acquisition and compared to bid and contract cost estimates.

There is an ever-increasing body of cost estimating tools, cost trade-off studies and cost-risk tasking. For modeling purposes, the growth of cost tasking is ignored relative to the baseline program. Baseline tasks (DDG-51) are shown below in Table 38. Inputs for developing these tasks are primarily weight based. Therefore, cost tasking relies on design characteristics (hull, weights, structures, machinery and combat systems) that are related to SWBS groups. For life cycle cost estimates, manning, ILS, and producibility are also incorporated. The output from costing is provided to programmatics as well as first order changes to those design characteristics that exceed cost thresholds for cost sensitivity such as structural weight and auxiliary systems.

Task Element	Concept	Preliminary	Contract	Detailed			
				Functional	Transition	Zonal	Production
Independent Cost Estimate & Unit Cost Report (ICE/UCR)	1	1	1	1	1	1	1
Class D/E/F Cost Estimate	1	1	1	1	1	1	1
Program Life-Cycle Cost Estimate	1	1	1	1	1	1	1
Class C Cost Estimate		1	1	1	1	1	1
Weight & Cost Engineering			1	1	1	1	1
Class B Cost Estimate			1	1	1	1	1

Table 38 Cost Estimates and Analysis Tasks

[136] Myron Ricketts, Manual for Naval Surface Ship Design Technical Practices, Naval Sea Systems Command, Washington DC, 1980, section 14.

5 *Process Model Sectors*

The following sections provide brief descriptions of the primary components of the naval ship design model. For specific model elements (equations and values) refer to the Vensim modeling code provided in chapter 8.7. A graphic representation of the design process model is shown in Figure 35.

5.1 Process Sector

The basic structure for all system dynamics product development models is the rework (or work accomplishment) structure. The structure may have several forms such as that shown in Figure 22 or Figure 34. The structure demonstrates that from an initial pool of work to do (TBD), work is accomplished at some rate. Based on a dynamically determined level of quality, some work is accomplished correctly and some requires rework. The incorrect tasks remain in error until discovered through a QA process and reassigned as work to do.

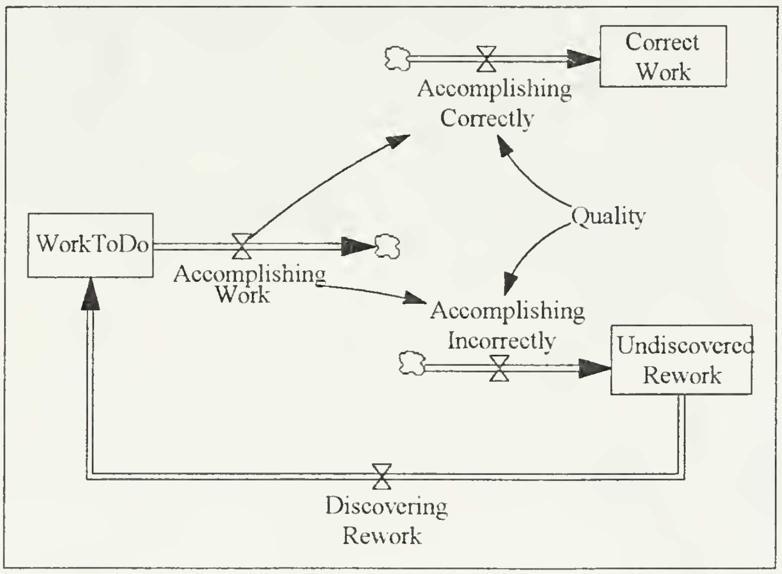

Figure 34 Work Accomplishment Structure

Several specific project models were examined for applicability to the naval ship design process problem. These previously developed models include the Ingalls Litigation Model (Cooper, 1980), Program Management Modeling System (PMMS) (Pugh-Roberts Associates, 1997), Software Project Model (Abdel-Hamid and Madnick, 1991) and Concurrent Development Model (Ford and Sterman, 1997). Each model was studied for behavior and policy elements applicable to naval ship design. Selected components of those models form the structural engine for the naval ship process model. Figure 36 shows this structure.

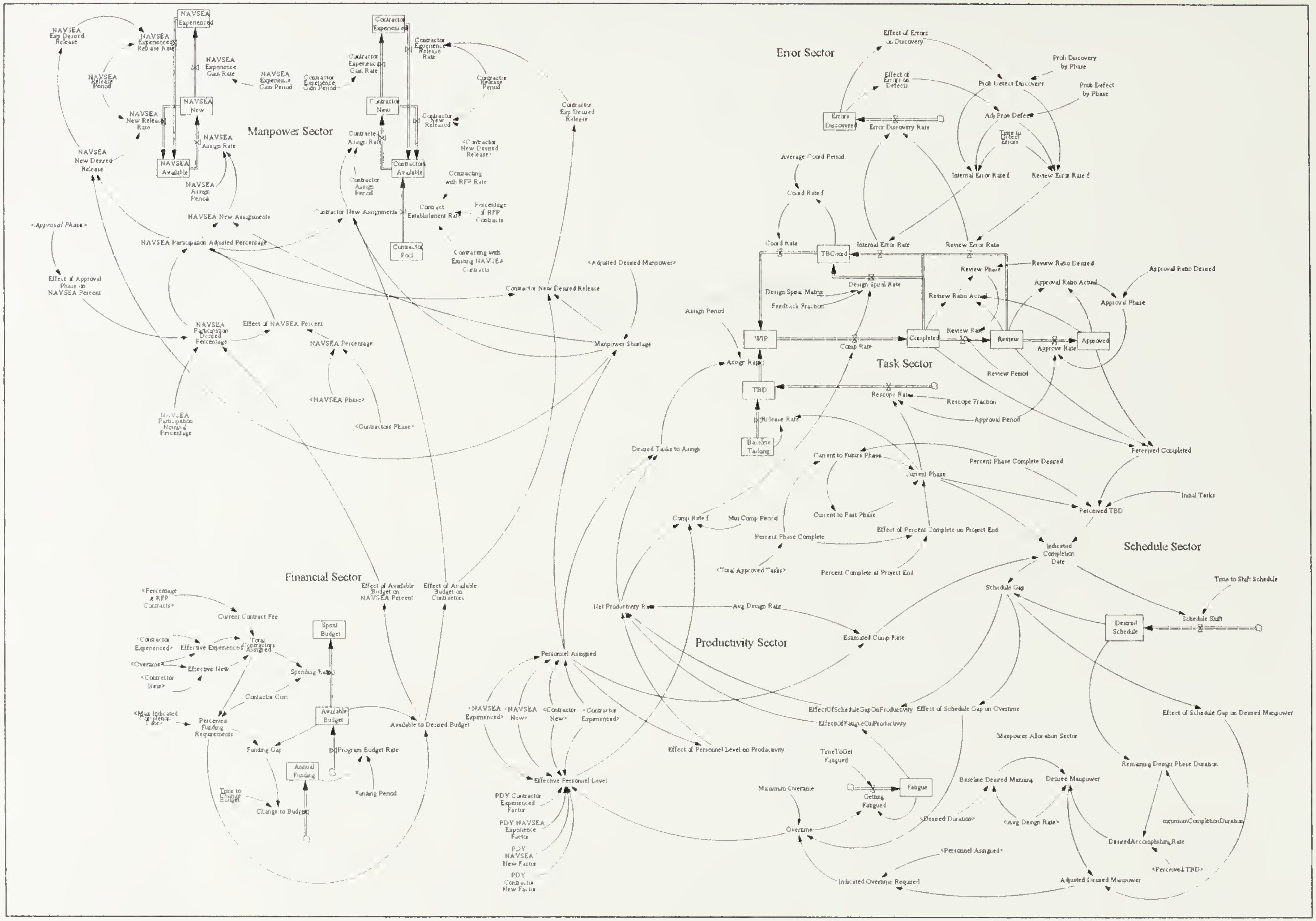

Figure 35 Naval Ship Design Process Model

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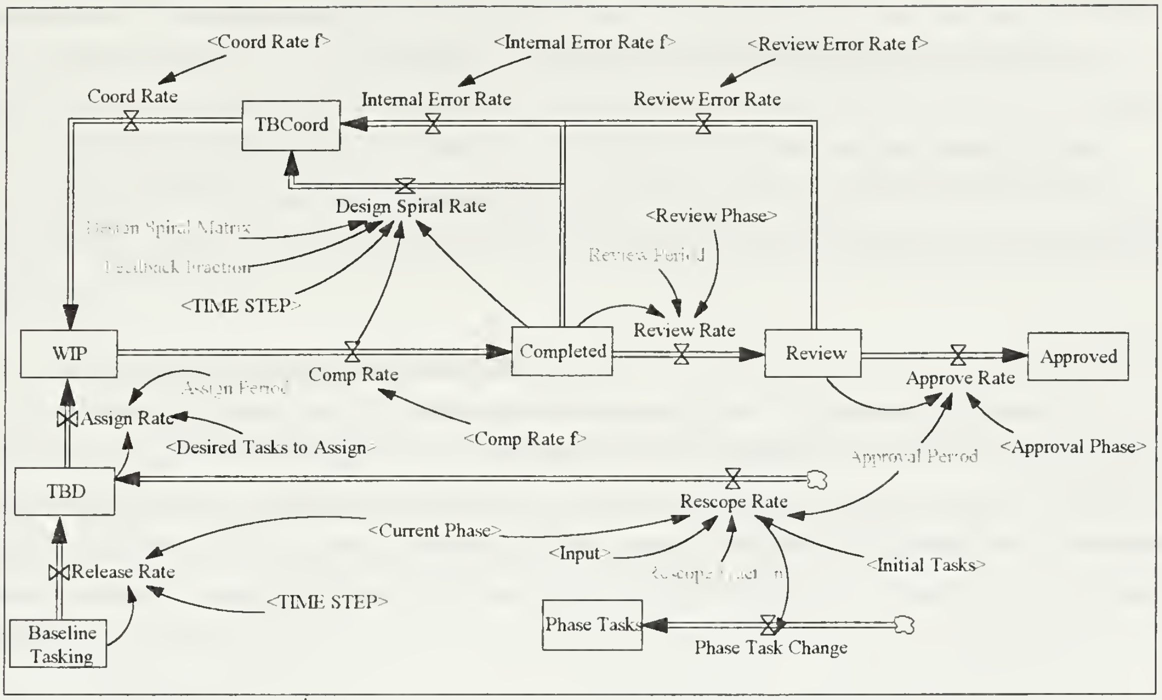

Figure 36 Naval Ship Design Process Model Work Accomplishment Structure

5.1.1 Primary Work Flow

The structure in Figure 36 demonstrates an operational view of the design process. At the beginning of the current design phase, some known level of baseline tasking is released as tasks to be done (TBD). Those tasks are assigned to the engineering staff and become work in progress (WIP). Based on an accomplishment rate (Comp Rate) tasks are completed. The completed tasks either require iteration (due to internal error discovery or design spiral relationships) or review. The reviewed tasks either require iteration (review error discovery) or release as approved tasks. Approved tasks are considered completed and not subject to further action. Note that this assumption may fail to fully capture rescope impacts which occur very late (high levels of approved tasks) in the design phase. The iterated tasks represent rework and are accumulated for coordination (Coord Rate). Based on a coordination rate, the rework is released back to the work flow as WIP. The structure also reflects the potential for scope growth (rescope rate). Rescope tasking enters the flow through TBD for assignment.

5.1.2 Review and Approval Factors

A key structure in the process is the inclusion of review and approval. For naval ship design projects, such review is required by law. However, the extent and duration is subject to interpretation. Review is considered an internal activity performed at the program level and below. Primary participants are program management staff,

activity staff (both NAVSEA and contractors) and interested parties. Approval is the acceptance of the design by external forces. Approval must include those organizations required to participate by law (DoN, DoD and program managers) and interested parties. As discussed in Chapters 1.1 and 4.4, the review process is a source of cycle time delay and growth. The required products for design review and the large numbers of review and approval levels were a primary concern to DAC study participants. During the DAC, data was gathered that described average approval and review periods for over 45 DoN projects. Additionally, limited data on CG-47 and DDG-51 approval and review periods was available. These values are shown in Chapter 8.5. Interviews (see Chapter 8.2) with process participants indicated that review and approval times (not error correction) are the primary sources of generated delays. As such, the model incorporates these delays directly as approval and review periods through first order control.

5.1.3 Error Generation and Detection

Errors form a significant source of feedback in a development process. As discussed in Chapter 3.1, generated errors (regardless of a specific cause) must be discovered and reassigned to correct. In system dynamics models, error generation is a dynamic event that may be coupled to forces such as schedule pressures, workforce experience, and fraction of job complete. QA efforts are also dynamic with improved QA productivity occurring as the project approaches completion Functional forms for error and QA efforts relative to those forces can be found in Abdel-Hamid and Madnick, 1991[137].

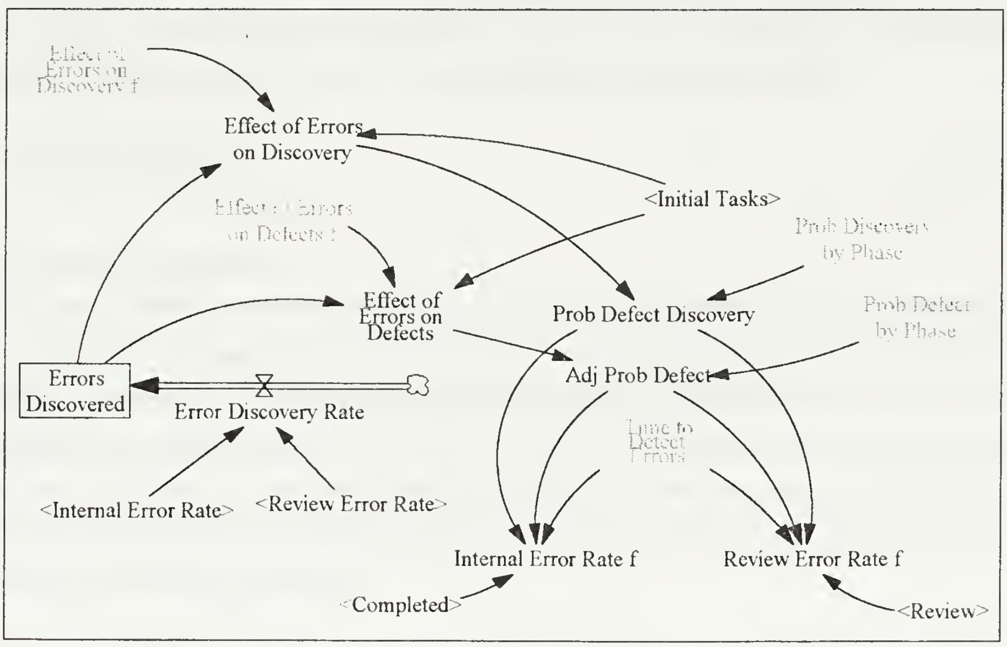

Figure 37 Naval Ship Design Process Model Error Sector

Figure 37 shows the error sector for the naval ship design model. Two dynamic modifiers were chosen for error generation and discovery. First, errors are more likely in earlier design phases than later. As such, the chosen

[137] Abdel-Hamid & Madnick, Software Project Dynamics: an Integrated Approach, Prentice Hall, New Jersey.

error fractions (as a fraction of total tasks completed) reflects decreasing rates as the project approaches detailed design. Additionally, as the total error discovered increases, the fraction of new error decreases. In error discovery, these factors work in reverse: as the project matures QA improves and as total errors increase QA effectiveness increases. The selection of baseline error rates (20% in concept design to 10% in detailed design) were based on interviews with personnel at both NAVSEA and Bath Iron Works (BIW) (see Chapter 8.2).

5.1.4 Design Feedback

The one structure of the naval ship design model not found in other system dynamics models is that of the design feedback loop. This dynamic reflects the interrelationship of the 23 specific design disciplines participating concurrently in the design process. Using the DSM developed in Chapter 4.3, tasks are reworked at a rate consistent with the following criteria:

- As task A is completed, a fraction of that task is "undone" by concurrent work in tasks to which task A is dependent
- Task A is "undone" at a rate not to exceed its own completion rate or
- "Undone" at the fastest rate of all its input tasks.

The feedback fraction represents the fraction of tasking that are "undone" by process concurrence. The value may be though of as either the average allowable margin for change at the given design phase or as 1 minus the fraction of performance and cost lock-in (see Figure 5.) Those tasks that are sent to iteration must be coordinated to determine what data has changed and what errors must be corrected. The coordination rate is (like the approval and review dynamic) a first order control through TBCoord and the average coordinate period.

5.2 Scheduling Sector

5.2.1 Desired Schedule

The concept of schedule encompasses the desired cycle time for the design project. It represents one of the three primary trade-offs of the project (Section 1.1.) It is by the selection of schedule that all other model variables are estimated and controlled. For instance, fixing schedules and design products produces a required manning level and the subsequent cost of those personnel. Schedule is not fixed over the life of the project. Consider Table 39. The desired schedule for contract award was allowed to slip many times over the course of the DDG-51 project and at increasing rates as the estimate date and the desired date converged. Table 40 further demonstrates the sliding of schedule dates over the course of the project.

Date of Estimate	March 15, 1983[138]	June 1, 1984[139]	December 9, 1991[140]
Desired Schedule	December 15, 1984	January 10, 1985	April 2, 1985
Change from Previous Estimate	---	1 month	3 months

Table 39 Schedule Estimates for DDG-51 Contract Award[141]

Date of Estimate	4/15/83	6/1/84	6/1/87	12/9/91
Concept Design Start		8/1/78		
Senior Review		2/1/82		
Command Review		12/15/82		
Concept Design End		3/31/82		
Preliminary Design Start		3/31/82		
SCIB		10/1/82		
Senior Review		12/1/82		
Command Review		12/15/82		
Preliminary Design End		5/13/83		
Contract Design Start		5/14/83		
DSARC			8/26/83	
Baseline Freeze			9/2/83	
Invoke Configuration Control	7/22/83		9/30/83	
Contract Design Circulation	12/5/83	3/28/84	3/28/84	
Senior Review	12/15/83	5/15/84	5/15/84	
Command Review	1/15/84	5/29/84	5/29/84	
Contract Design Reading Session	3/5/84	6/1/84	6/15/84	
Contract Design Signature	5/25/84	6/9/84	6/29/84	
Contract Design End		3/1/85		
Contract Award	12/15/84	1/1/85		4/2/85
Lead Ship Launch		5/1/88		9/16/89
Lead Ship Delivery		9/1/89	7/1/89	4/29/91

Table 40 Key Program Dates and Schedule Shifts[142]

To model this behavior, the following generic elements are applicable (Figure 38.) From an equilibrium condition (schedule gap is zero), assume a perturbation occurs and estimated completion exceeds scheduled date. Initially, gap increases, pressure to increase workforce levels increases, workforce increases, accomplishment rate increases, project duration decreases, estimated date decreases and gap decreases…a balancing system through estimated completion date. Simultaneously, as the estimated date exceeds the desired date, the desired date updates to match estimates. The time to change schedule represents the average time required to absorb half the schedule gap. As the desired schedule increases, the gap decreases, pressure to increase manpower decreases, manpower decreases and, ultimately, the estimated date slides further…a reinforcing system through desired completion date.

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138 CAPT J.J. Fee (USN), US Navy letter 50C/JJF Serial 5032-042, April 15, 1983.
139 Naval Sea Systems Command. Ship Design Project Histories: Volume II 1980-1989, estimated edit date June 1984, page 2.8-5.
140 Joe Daley, PMS-400B Program Office, Washington D.C., correspondence dated December 9, 1991.
141 See footnotes 138, 139, 140.
142 Ibid.

Based on the observed schedule (Table 40), the initial values for the baseline design model are established (Table 41.) The adjustment time, as input to an exponential decay function, may be approximated as follow:

$$\text{AdjustmentTime} = \frac{\text{TimeToCloseGap\_}}{3}$$

The Time to Close Gap is the time to observed phase end. Thus, an Adjustment Time of 12 months is consistent with the observed results.

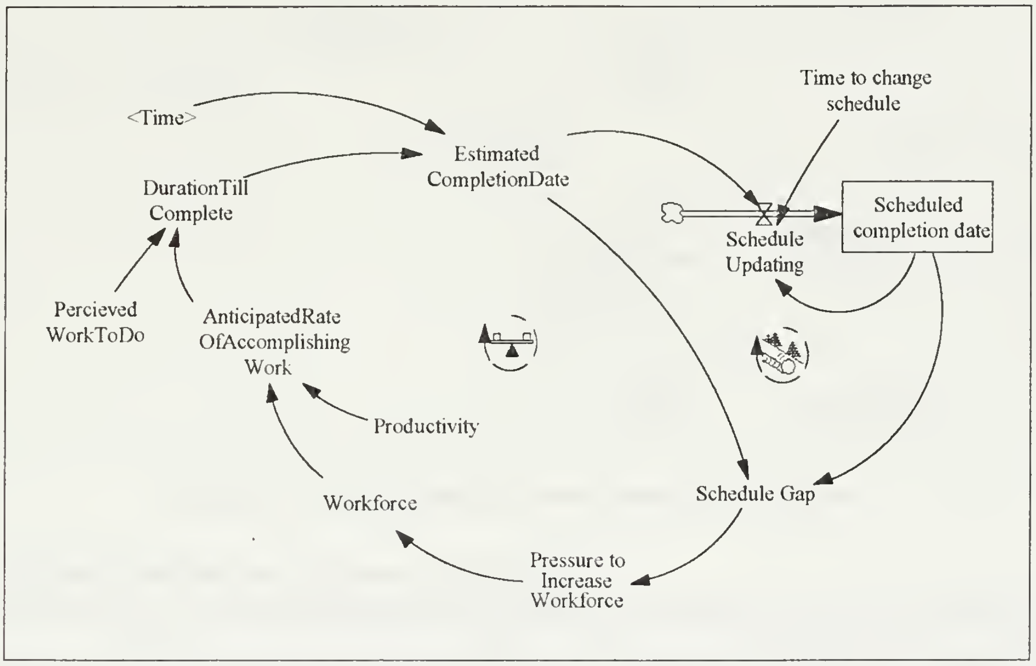

Figure 38 Generic Schedule Model[143]

Design Phase	Concept	Preliminary	Contract	Lead Ship	Manufacturing
Initial Schedule Projection (months from start)	36	48	60	72	78

Table 41 DDG-51 Design Process Model Desired Schedule Initial Values

The generic structure is reflected in the naval ship design process model as the schedule sector (Figure 39). Like the generic structure, tasks remaining are compared to the available manpower and nominal design rate to determine a projected completion date. This date is compared to the desired date to generate a gap. Based on the gap, adjustments are made to manpower, productivity and overtime (see Figure 35 to observe those feedback links).

One slight modification is noteworthy. Instead of measuring progress by what remains, naval ship project managers measure progress by what is done. Specifically, the perceived tasks completed is a function of completed tasks (completed, reviewed and approved). The tasks to be done are then generated by comparing completed tasks to the expected total tasks for the current phase: initial tasks times the percent phase complete desired. Percent

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[143] Jim Hines, "Molecules of Structure Version 1.3", LeapTec and Ventana Systems, 1997, page 85-86.

phase complete desired is the fraction of total tasks that must be completed to allow designers to proceed to the next iteration. This alternate structure can be found in other project management models.[144]

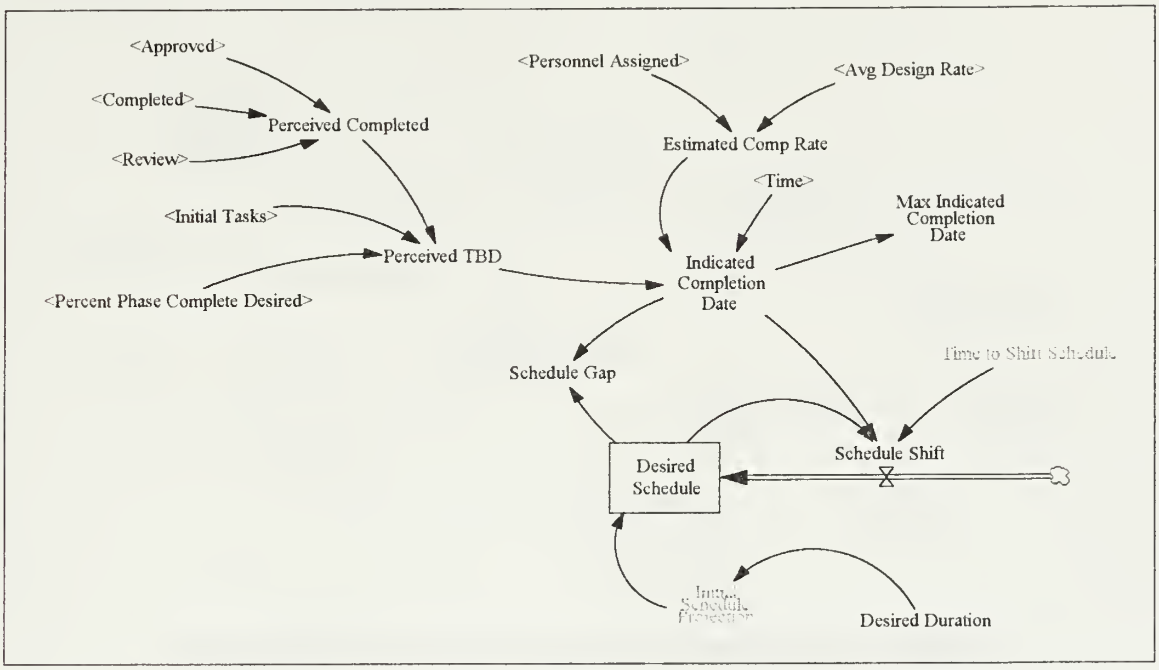

Figure 39 Naval Ship Design Process Model Schedule Sector

5.2.2 Phase, Review and Approval Initiation

Due to the inclusion of multiple design phases (concept design, preliminary design, contract design, lead ship detailed design and manufacturing engineering design) and multiple stages within a single phase (tasks in progress, tasks under review, and tasks under approval), it is necessary to establish a structure to initiate subsequent sequences and close previous ones. The phase initiation structure is shown in Figure 40. Based on the comparison of approved tasks to total tasks for the phase, the percentage complete is generated. That percentage is compare to the required percentage necessary to proceed to the next phase. When the current phase percentage is satisfied, a Boolean operator (Current Phase) is set to 1 for the next phase to start the release of new tasks. Simultaneously, Current Phase is set to 0 for the phase being completed. This prevents the release of further tasks and resources to the completed phase. A parallel structure is present for release of tasks to review (completed tasks become available for review) and approval (reviewed tasks become available for approval). However, unlike the Current Phase variable, approval and review operators do not stop previous segments from continuing.

[144] Abdel-Hamid & Madnick, Software Project Dynamics: an Integrated Approach, Prentice Hall, New Jersey.

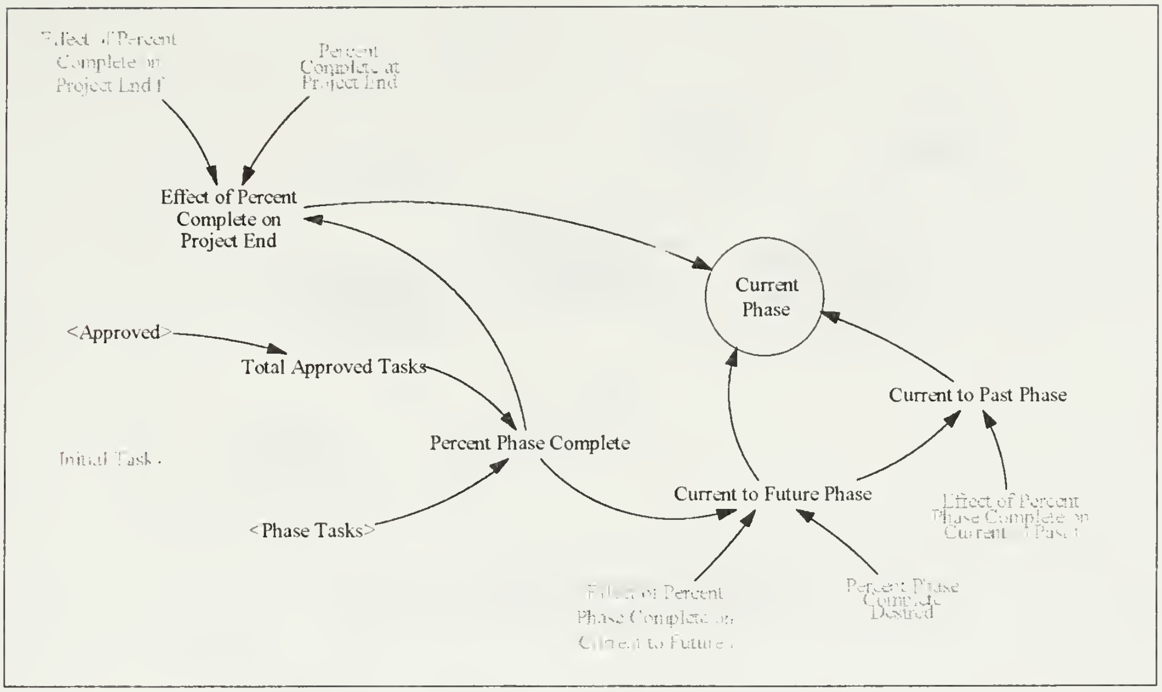

Figure 40 Naval Ship Design Process Model Phase Initiation Structure

5.3 Productivity Sector

Productivity is the measure of the effective rate by which available manpower is able to complete assigned tasking. Figure 41 shows an example of a generic productivity calculation. This structure shows how a nominal productivity level (normal productivity) is influenced by factors such as fatigue, schedule pressure (or schedule gap) and work adequacy (or fraction of design change). Productivity as shown here is measured as the number of tasks completed per person per unit time.

Productivity is a very difficult quantity to measure. This is true because observed productivity represents the work rate after the modifications by dynamic influences (fatigue, schedule pressure, etc). As such, nominal productivity represents a fraction very different than that which is observed. Consider the naval ship design process model productivity functions (Figure 42). Like the generic structure, numerous dynamic influences are included: fatigue, organizational size, and schedule gap. The average design rate is included to represent the nominal productivity level. This value actually represents the observed rate for a given project and is calculated as:

$$\text{AverageDesignRate} = \frac{\text{TotalTasksPerDesignDisciplinePerPhase}}{\text{TotalPersonnelPerDisciplinePerPhase} \cdot \text{PhaseDuration}}$$

This rate would represent the value used by program managers to assess progress or model the process in scheduling programs (CPM/PERT models). For the DDG-51, the average design rates are calculated and shown in Chapter 8.5. However for the process model, this rate must be adjusted to reflect the actual baseline rate absent of dynamic influences. The observed rate is multiplied by an adjustment (Adjust Rate) in the naval ship model to provide calibration of the observed rate in order to reflect the nominal rate of productivity.

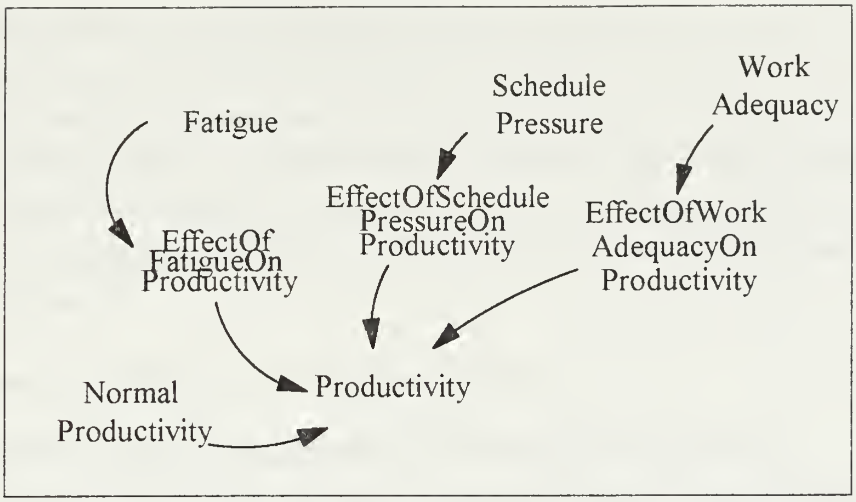

Figure 41 Generic Productivity Structure

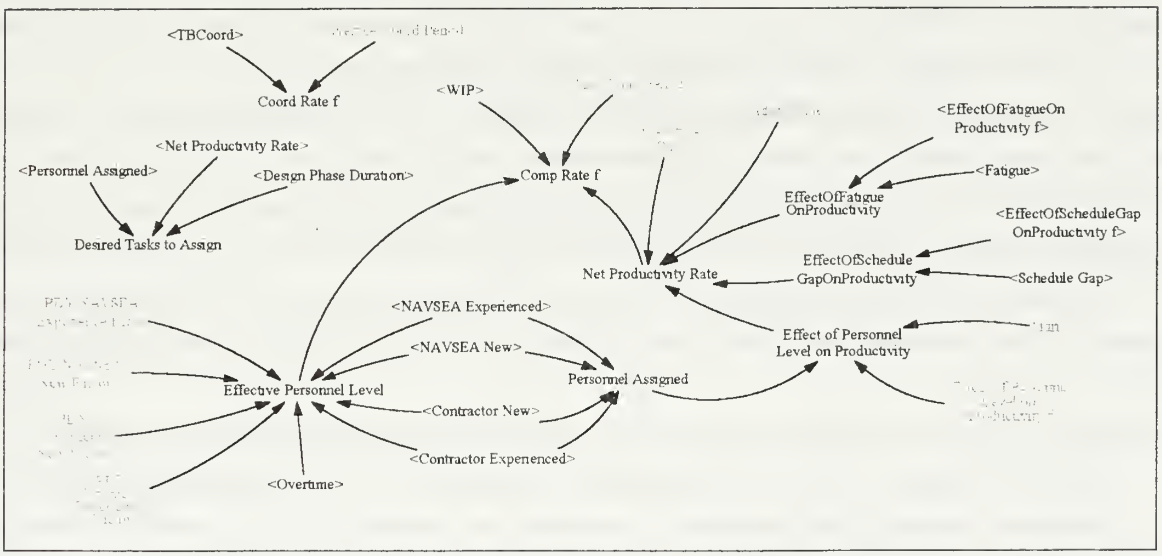

Figure 42 Naval Ship Design Process Model Productivity Sector

With the effective productivity rate established (Net Productivity Rate), it is multiplied by the effective personnel level to provide a completion rate (Comp Rate) by which the pool of WIP is completed. Note that the Comp Rate has a ceiling rate (maximum rate of completion) provided by the first order feedback through WIP and a minimum completion time for a single design task. That minimum rate is estimated as 1 month in the model.

A similar structure is shown for the rate at which tasks in rework (TBCoord) are completed. Additionally, a structure for the initial assignment of tasks is provided based on the perceived completion rate for available tasks (personnel assigned times net productivity rate of those personnel) and the desired period of design completion (Design Phase Duration).

The effective personnel available for assignment is modified by three inputs. First, the basic manning level represents the total number of NAVSEA and contractor personnel assigned to a particular design phase and design

discipline. However, not all men are created equal. Rather, a second modification is necessary to reflect the differences in project experience among the personnel. It is assumed that although all engineers and designers are equally skilled, those who are with the project for more than six months are more productive (by an assumed factor of 20%) due to experience with the design material and the design organization. Finally, as schedule pressure increase, design managers may begin to authorize overtime work for personnel. As a first order dynamic, overtime has the effect of fractionally increasing the personnel level (by as much as 150% for limited durations) without the need to actually hire new, inexperienced designers. However, the short term impacts of overtime may be negated by second order fatigue impacts.

5.4 Manpower Availability and Assignment Sectors

5.4.1 Naval Ship Design Organization and Resource Structure

The Design team is characterized by government and industry participants. The level of participation transitions from mostly governmental to mostly commercial over the course of the program. Figure 43 shows the increasing fraction of contractor to NAVSEA effort that took place over the course of the DDG-51 design program. In this case, the NAVSEA levels were relatively consistent throughout the program, but the participation of contractors (both private and other government agencies) increases exponentially during the program. The impacts of this transition (shown in Figure 5) are discussed. Such transitions are natural when considering the goal of each stage of the process. The organization that results from the transitions and manning levels must reflect by the need to manage the design and to assign appropriate resources to design tasks. As presented in Chapter 4, the design tasks are naturally broken into design disciplines (23 are listed.) These disciplines contain the structure for manpower organization and design interfaces. A comparison of design disciplines and manning levels is shown in Figure 44.

Consider the organizational charts for the DDG-51 program (Figure 45, Figure 46, Figure 47, Figure 48). Each element of the organization represents a portion of the design process structure captured in the design disciplines. For instance, Figure 45 represents the programmatic organization and its linkages to operational requirements generation (CNO), engineering resources (NAVELEX, NAVSEA and SYSCOMs), and the design itself (Ship Design Manager and Combat Systems Engineer). The Ship Design Manager (SDM) and his/her organization is shown in Figure 46. This organization reflects the different task groups (machinery engineering, hull engineering, integration and specifications, etc) under which the specific task disciplines are completed. Figure 47 shows the combat integration and design organization and its linkage to the design through the program manager and SDM. Finally, Figure 48 demonstrates the organization for cost assessment and control. Note the close ties between cost and weight necessitated by the costing models of that time. For early design stages, the participation of shipbuilders is limited as shown in Figure 49.

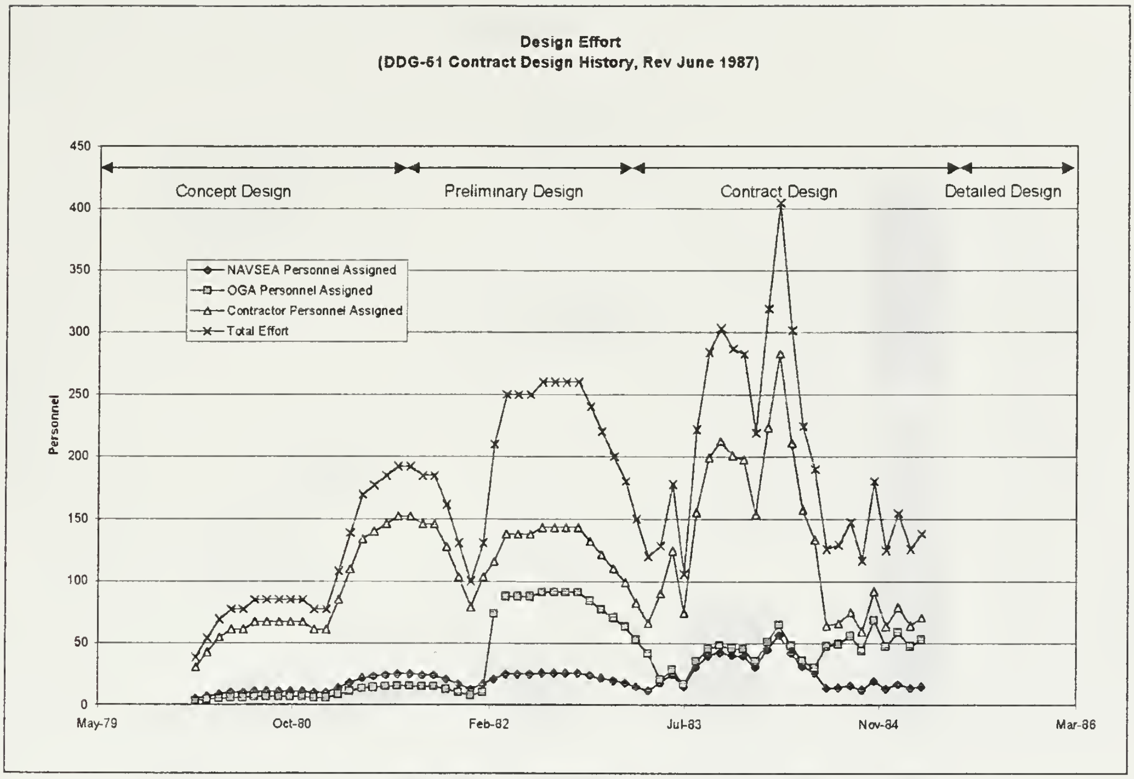

Figure 43 DDG-51 Total Design Effort[145]

[145] Data is complied from documentation listed in Chapter 8.4.

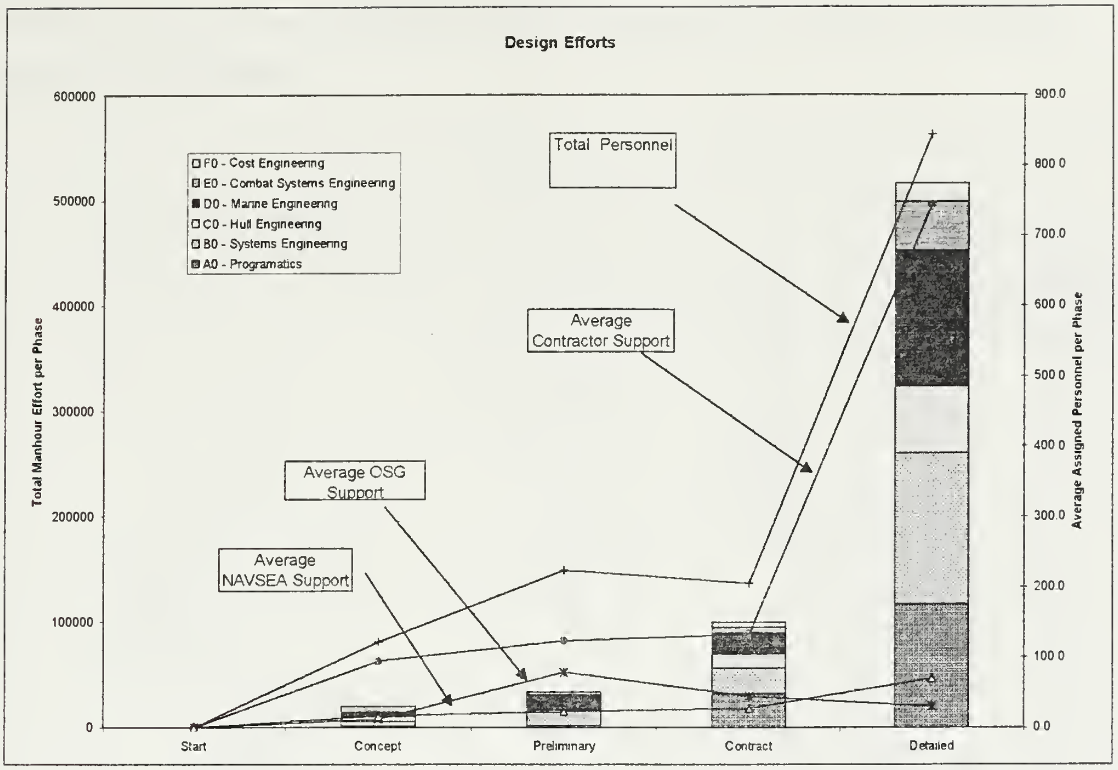

Figure 44 DDG-51 Manpower Transitions and Design Task Growth[146]

As the design transitions to industry, the organization must likewise transition. The government design team in later stages includes a reduced level of those organizations discussed above and resident Supervisor of Shipbuilding (SUPSHIP) organization that provide contract oversight. The industry participants (coordinated through the shipbuilder) include:[147] Shipyard Management Teams (Design Management), Functional Design Teams (Systems Engineering and Component Integration), Zonal Design Teams (Transitional Design CAD extraction and Zonal Design and Manufacturing Design Extraction), and the Materials Management Team. Within detailed design, shipbuilders level load teams to maximize resources (teams, designers and engineers, computers) while providing production facilities with design products in a timely fashion. Detailed design products must be completed Just in Time (JIT) to accommodate design changes with minimal impact to completed design products. In other words, design products are not completed unless manufacturing is ready to proceed.[148] Typical design effort for the DDG-51 included in the model consists of a team of 372 engineers and designers working in two shifts (244 in first shift, 113 in the second.) The designers are organized into 8 zonal teams: 3 hull specialty teams, 3 machinery specialty teams, and 2 electronic (combat systems) specialty teams. The teams work eight zones concurrently in design and no more than four zones transitioning to the next subphase at any given time. Teams to provide logistics

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[146] Ibid.

[147] C. R. Lloyd, "Design Process for the AEGIS Destroyer Program", Presentation, Bath Iron Works D87 Class Design Office, November 18, 1997.

[148] David Hinds, interview at Bath Iron Works, Brunswick, ME, November 15, 1997.

management (ordering and parts management) and design management (ECP management, information management, etc) are included.

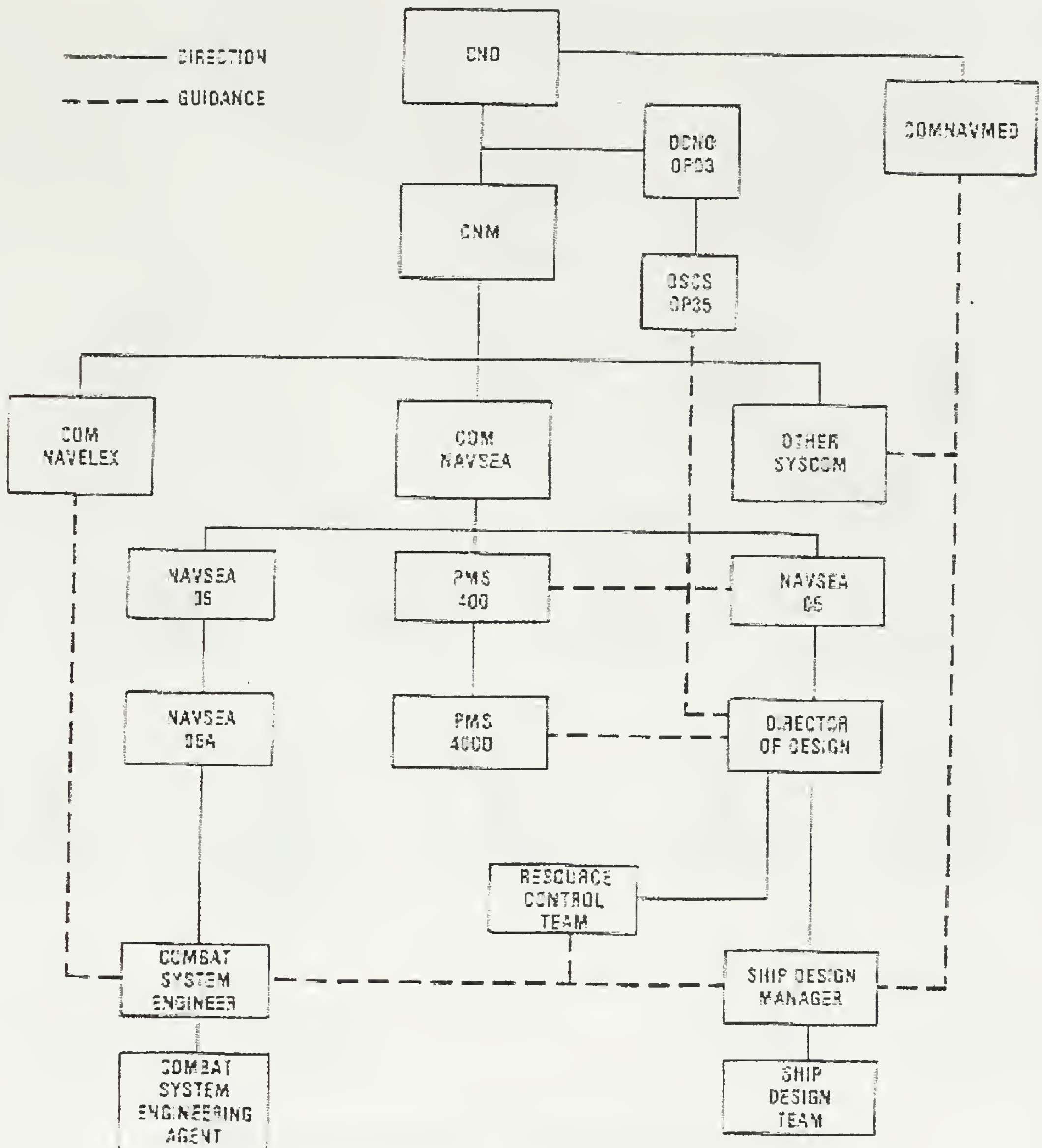

FIGURE 2-1. DDG 51 SHIP DESIGN COMMAND AND PROGRAM ORGANIZATION

Figure 45 DDG-51 Ship Design Command and Program Organization[149]

[149] Andy Summers, Contract Design History for the Guided Missile Destroyer (DDG 51 Class), Naval Sea Systems Command, Washington DC, June 1987, page 2-27.

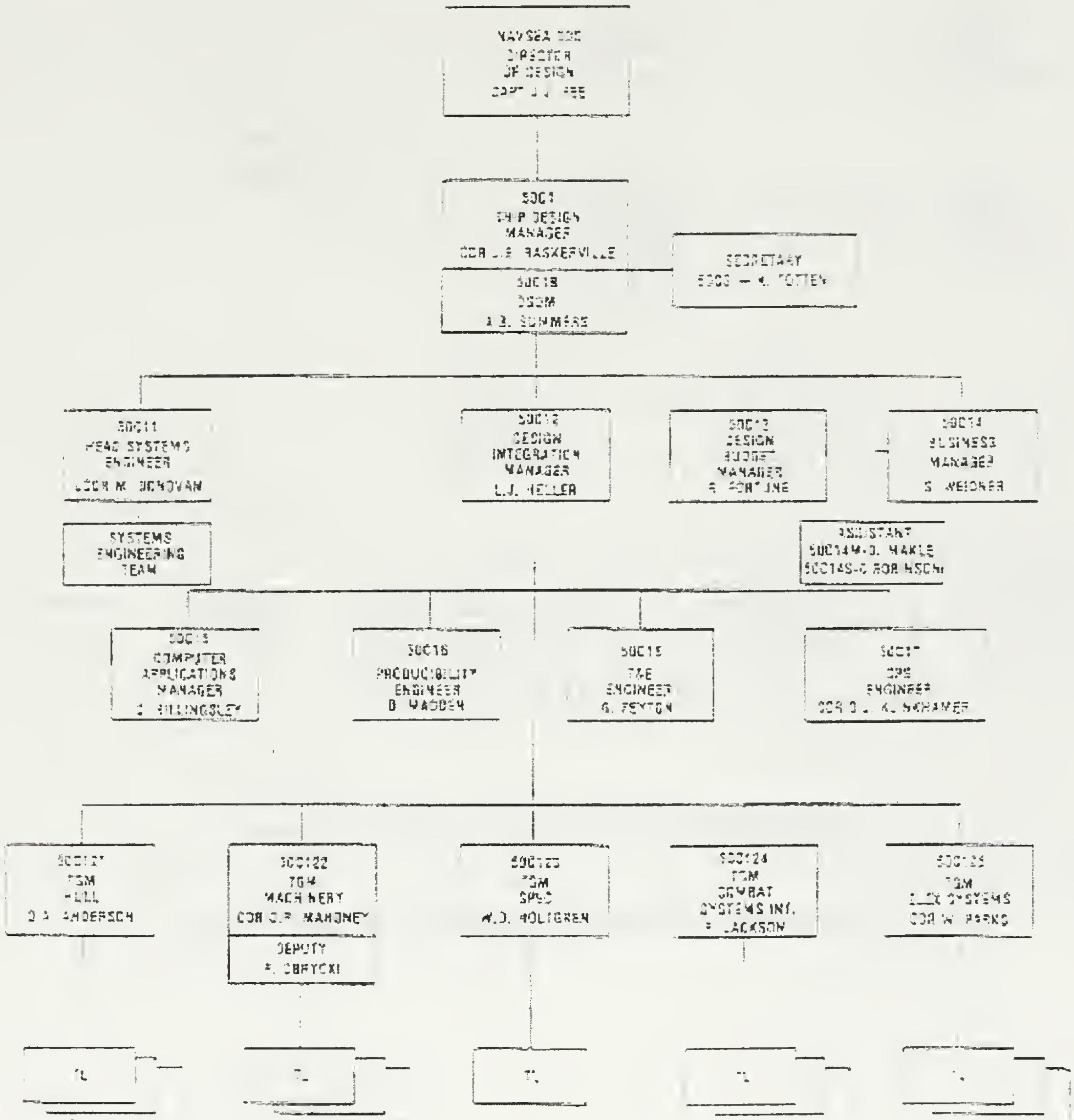

FIGURE 2-2. DDG 51 SHIP DESIGN TEAM ORGANIZATION

Figure 46 DDG-51 Ship Design Team Organization[150]

[150] Ibid., page 2-28.

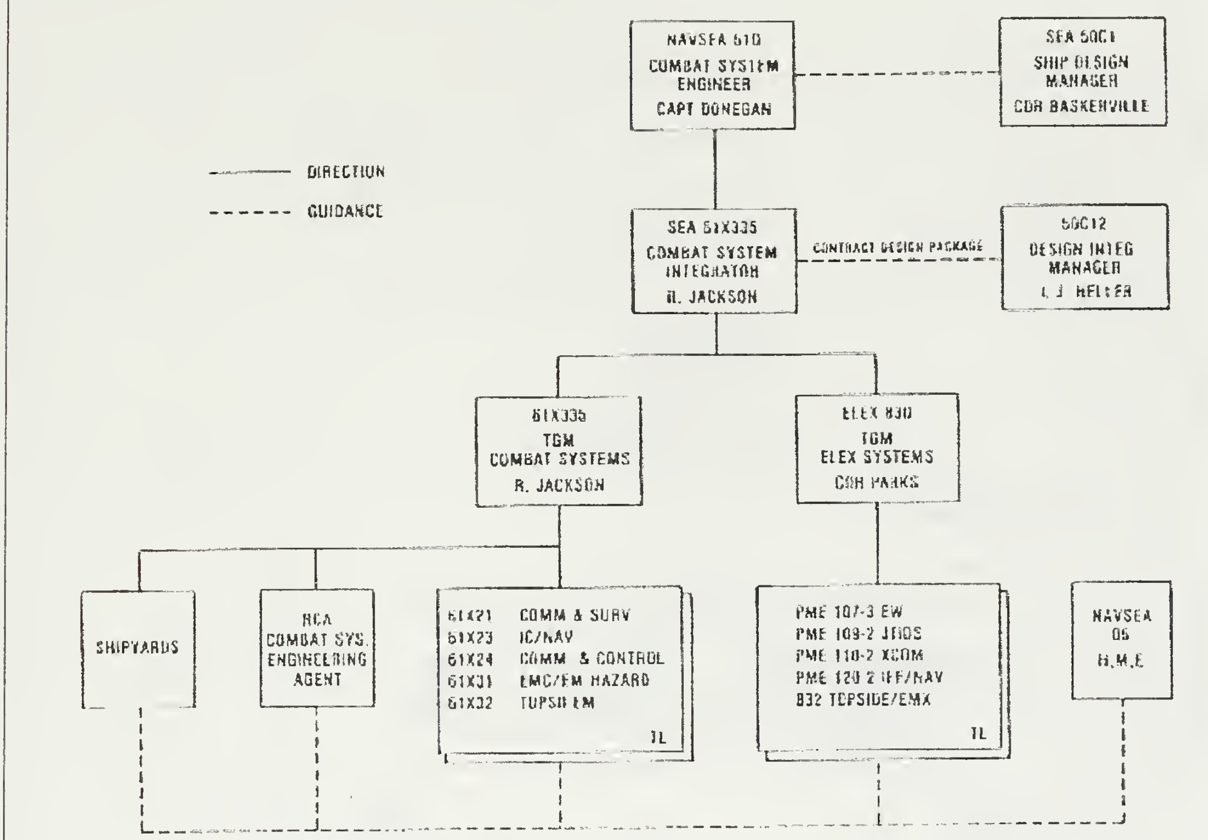

FIGURE 2-3 COMBAT SYSTEM ENGINEERING ORGANIZATION

Figure 47 DDG-51 Combat System Engineering Organization[151]

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[151] Ibid., page 2-29.

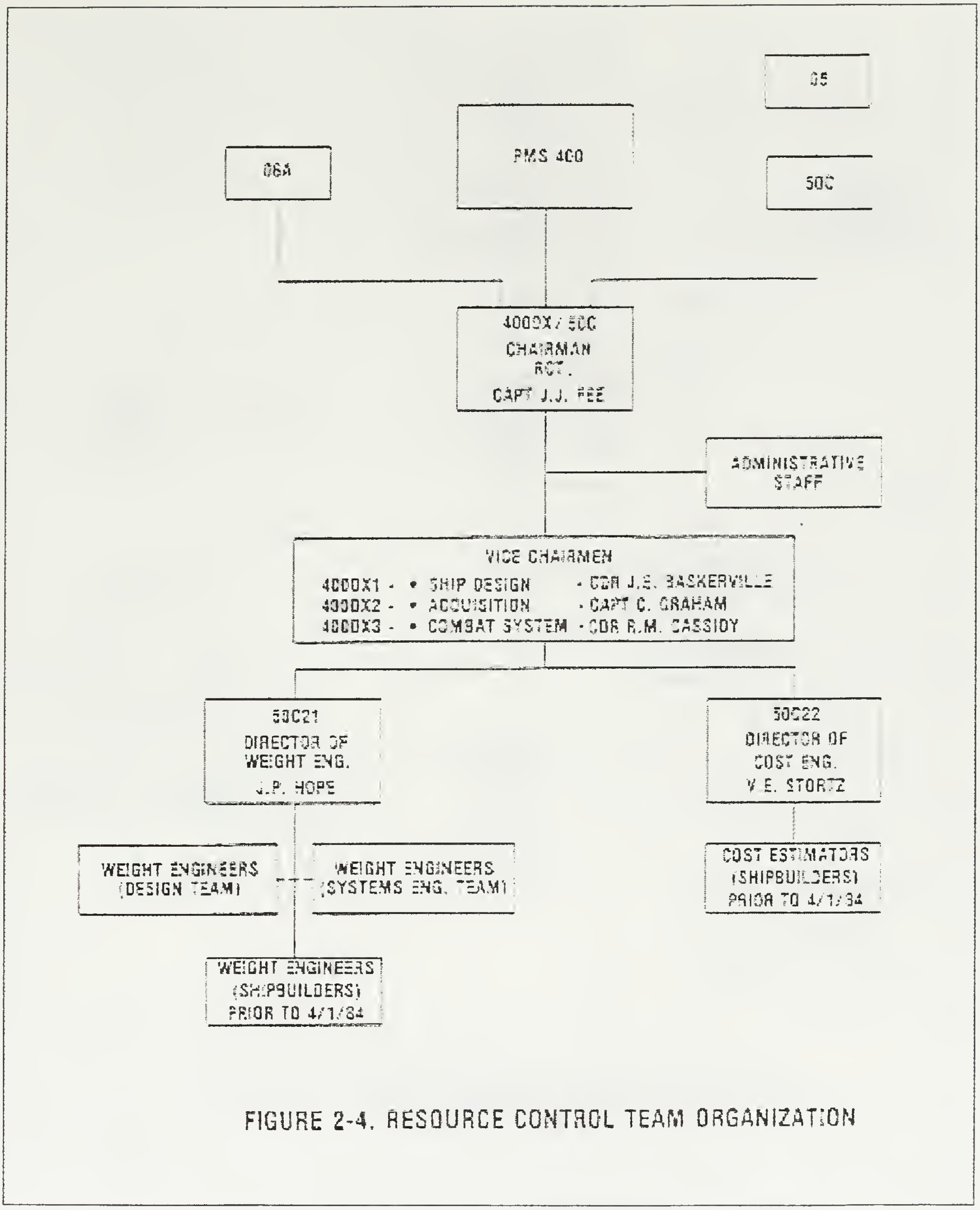

FIGURE 2-4. RESOURCE CONTROL TEAM ORGANIZATION

Figure 48 DDG-51 Resource Control Team Organization[152]

[152] Ibid., page 2-30.

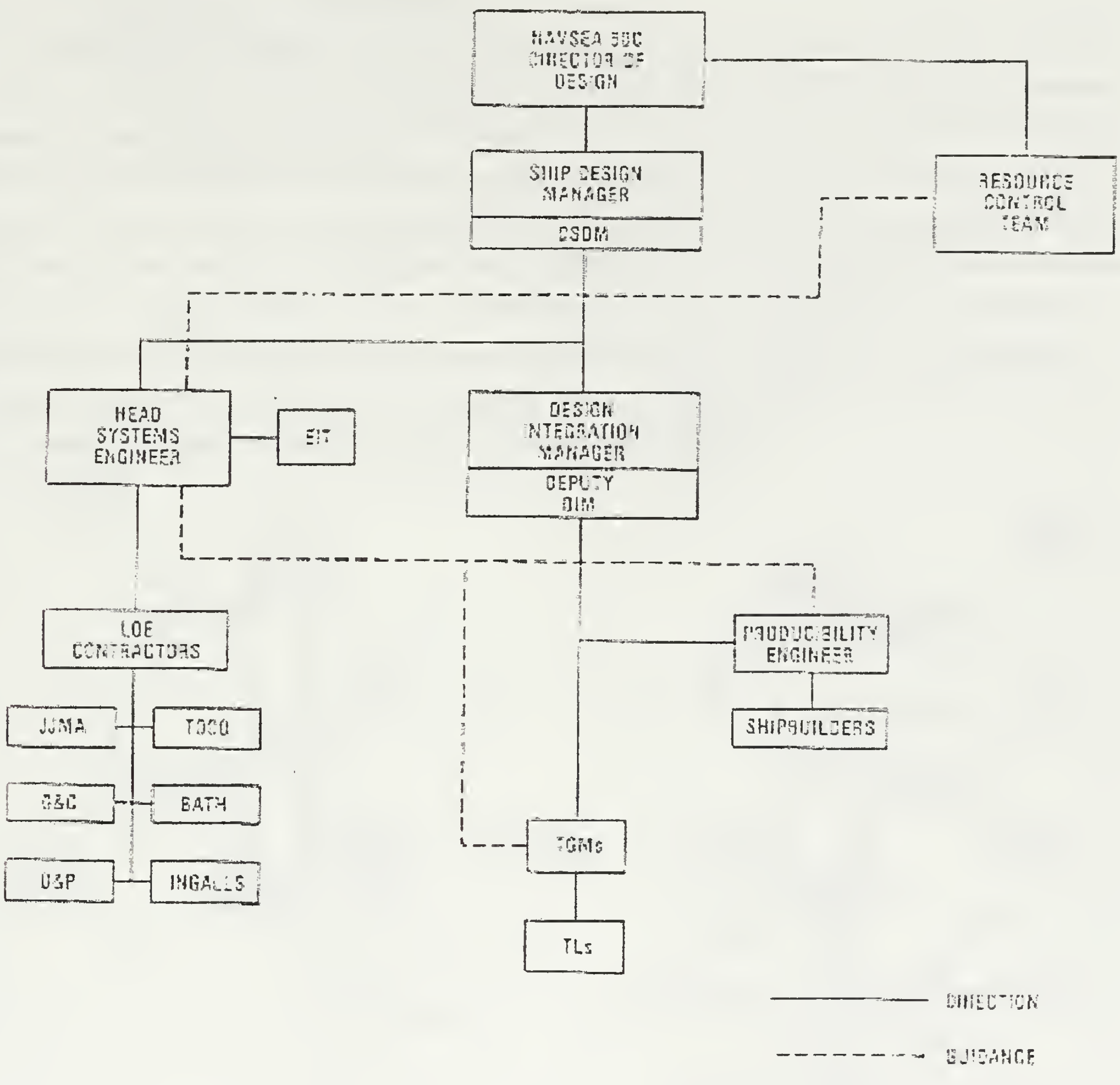

FIGURE 2-5. SYSTEM ENGINEERING TEAM RELATIONSHIP TO DDG 51 DESIGN TEAM

Figure 49 DDG-51 System Engineering and Ship Design Team Relationship[153]

[153] Ibid., page 2-31.

5.4.2 Manpower and Adjustments

The general dynamic behavior of resources is characterized by step increases in manpower from Concept through Detailed Design, ascending and declining effort within each phase, and small numbers of governmental personnel outsourcing large fractions (50 to 75%) of design effort to contractors. This is captured in the naval ship design process model by splitting manpower into two flows: NAVSEA and Contractors. Figure 50 shows this structure. NAVSEA personnel are those personnel that are considered free to the program from a budget stand-point. However, there are fewer NAVSEA personnel available and the first order assignment of personnel is more difficult as fewer become available. Contractor personnel flows include all those personnel that require budget expenditures to work. They include other government agencies (OGAs) such as the Navy labs, ship design contractors such as JJMA or AME, and shipyards such as BIW. As discussed previously (see Chapter 5.3), the flows explicitly include the maturing of designers over the course of the project.

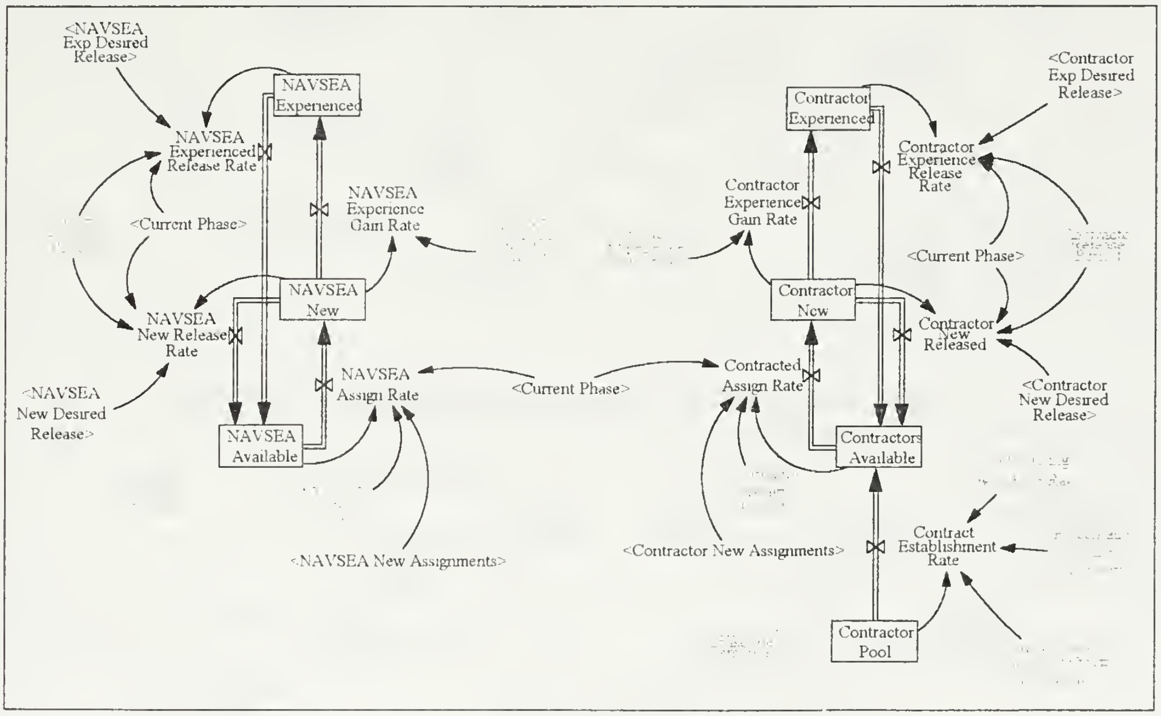

Figure 50 Naval Ship Design Process Model Manpower Sector

Given the available personnel, it is necessary to determine the desired number of personnel to be added or removed from those flows (Figure 51) and the distribution of personnel requirements between government and private resources (Figure 52). Several noteworthy properties are demonstrated in these structures. First, overtime is modeled to reflect the means by which managers assess overtime needs (Indicated Overtime Required and the Effect of Schedule Gap on Overtime) and the impact of overtime for extended periods on productivity (Fatigue). Fatigue is a stock because the accumulation of fatigue does build over time and takes time to decrease again. Secondly, manpower loading levels (seen Figure 43) show decreases in both total effort and percentage of contractors when approval stages begin. Table functions for the effect of approval phase on desired manpower and on NAVSEA

fractions are also included. The model determines a desired manpower level, adjusted by these effects, and uses this value to requisition new personnel or release personnel based on a perceived manpower gap (manpower shortage). The shortage is distributed by the desired fraction of NAVSEA personnel to be hired. If personnel are to be released, the model attempts to release new personnel prior to experienced manpower. This effect is included based on interviews with managers from NAVSEA and BIW.

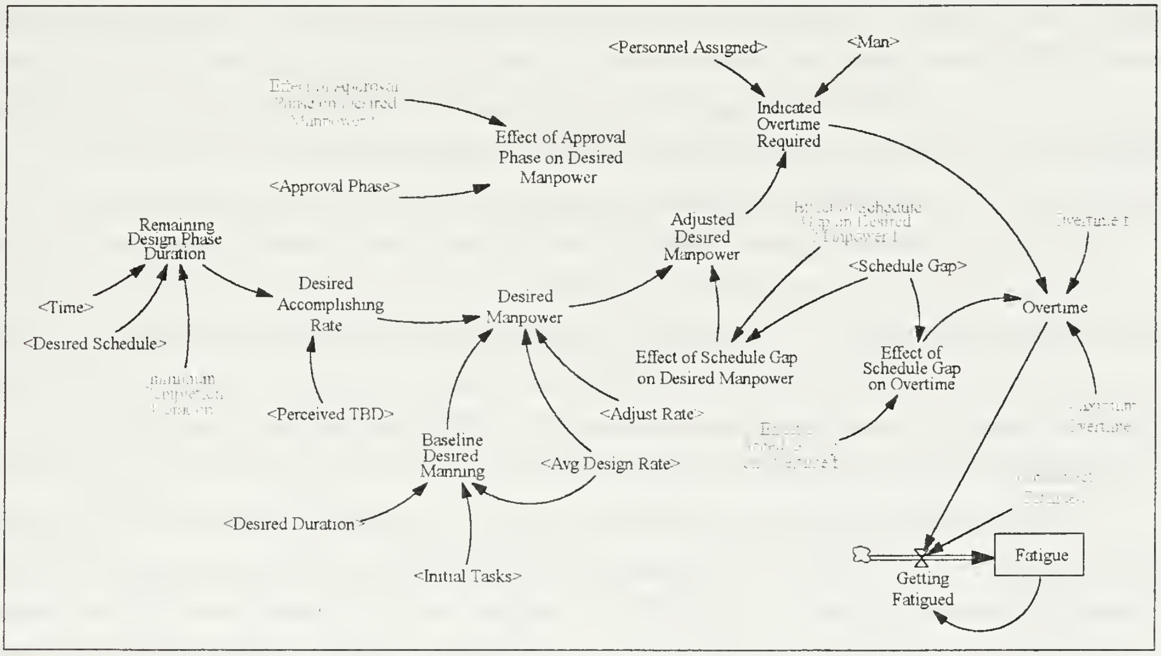

Figure 51 Naval Ship Design Process Model Desired Manpower Sector

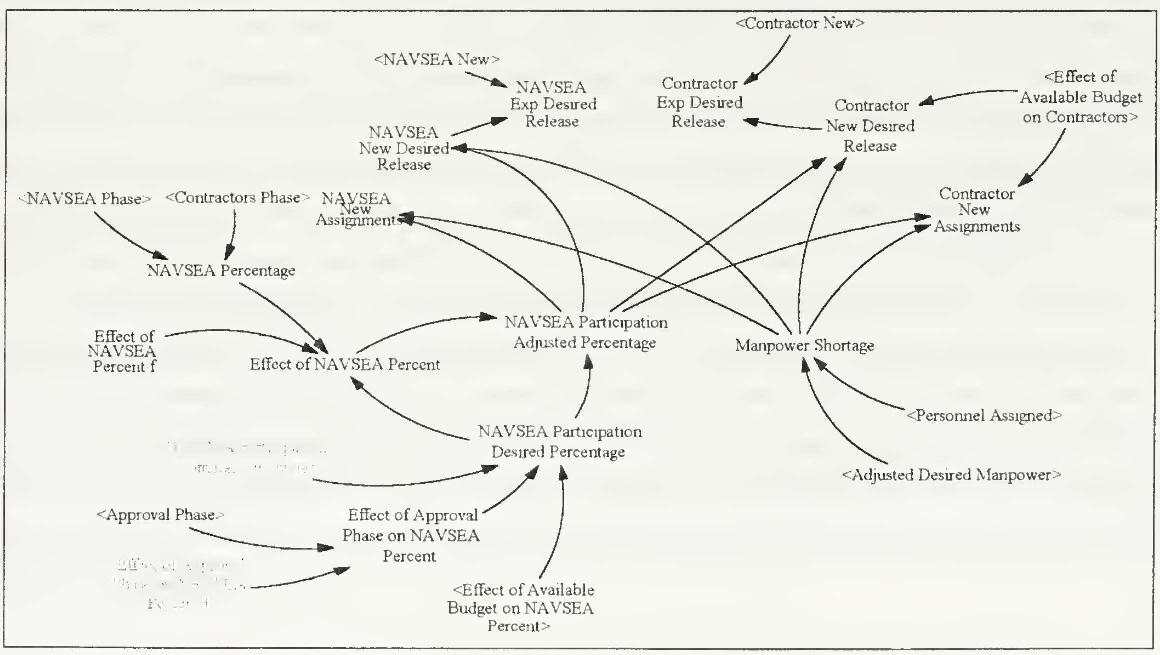

Figure 52 Naval Ship Design Process Model Manpower Allocation Sector

5.5 Financial Sector

The financial sector is the link between the design process model (schedule) and the available design budget. This process fits within the context of the formal DoD budgeting process: the Planning, Programming and Budgeting System (PPBS). The PPBS is a multi-year budgeting system that addresses all areas of military budget including both operational expenditures and acquisition. Program managers must interact with the PPBS to secure funding for future design and acquisition costs and continue to justify current expenditures.

The system consists of three distinct phases. During the Planning Phase, mid term and long range defense goals are assessed against perceived threats. This is similar to the dynamics seen in Chapter 2.1. Based on results of this analysis, the National Security Council issues the National Military Strategy Document (NMSD). The document is issued in July of odd numbered years. Between then and November 30th of the same year, the document is reviewed and re-issued as the Defense Planning Guidance (DPG). The document defines the fiscally constrained force structure into which the program manager must attempt to secure a portion of funds.

The second phase is the Programming Phase. This phase establishes the allocation of funds to the specific force elements that must be supported. There are eleven force elements which include strategic forces, general purpose forces, research and development, etc. The goal of this phase is to establish the optimized mix of manpower and equipment required to satisfy the national defense posture. By April of the next year (even year) Program Objective Memorandums (POMs) are prepared. The POMs reflect "a detailed expression of proposed programs by program element, schedules and funding 6 years into the future, with force levels 3 years beyond that...Each POM submission is a modification of the approved FYDP (Future Years Defense Program), updated to reflect current guidance from OSD (Office of the Secretary of Defense), with 2 fiscal years being added during each (POM) cycle."[154] By September, all POM issues are debated and approved with the Secretary of Defense approving these submissions as the basis for the Budget Estimate Submission (BES). The program manager, based on the current and future needs of his or her program, seeks to influence the POM submission to gain additional funding for the program as necessary. However, the nature of this system means that actual funding requests are not realized for at least 2 years from submission and possibly 4 years if the submission falls at the end of the POM cycle.

The final phase is Budgeting. From September through December, the BES and POM are assessed for categorical allocations to five primary budget categories: RDT&E, Procurement, Operation and Maintenance, Military Personnel and Military Construction. During this period final budget adjustments known as Program Budget Decisions (PBDs) are performed to account for cost factors, risks in projections, the timing of related events, jointness of requests, and uniformity. The final budget is submitted to the President the first Monday after the 3rd of January in the next year (odd). The budget is debated and approved for activation the following fiscal year (October of the year of submission).

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[154] Defense Systems Management College, The Program Manager's Notebook, Fort Belvoir, VA, June 1993.

The obvious delays in the timescale of the PPBS must be accounted for in the development of the naval ship design model. Coupled with the target profile for engineering expenditures during the design process, the PPBS manifests itself as a funding delay when increased budget needs arise to meet design schedule deadlines. Consider the typical engineering cost profile for a surface combatant program shown in Figure 53. Based on past cost profiles (such as is shown below), the desired schedule and the complexity of the design program (total tasks to complete), the program manager must submit a budget request through the PPBS. Funding is not granted in excess of perceived needs, so the program manager are constrained to a fixed schedule and budget. However, as process dynamics cause the schedule to slide and the engineering cost fluctuate as does manpower loading (Figure 43), funding shortfalls can occur. The time required to overcome the shortfalls is equivalent to the duration of the PPBS.

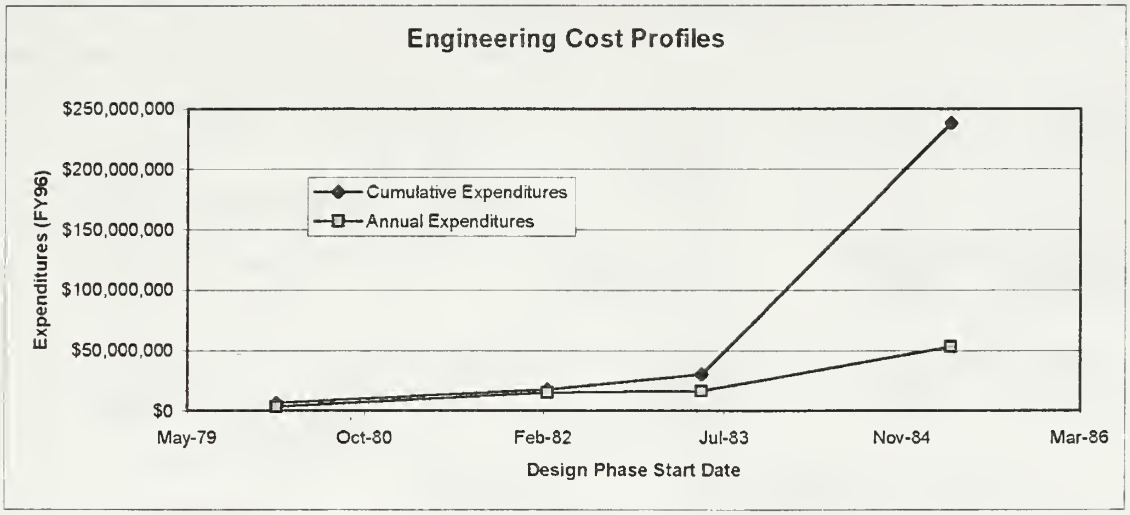

Figure 53 DDG-51 Engineering Expenditures[155]

Figure 54 shows the dynamic budgeting and allocation flow for the naval ship design process. The delays from the PPBS are modeled as a first order delay through Change to Budget and Time to Change Budget. The Time to Change Budget is set to 2 years to reflect the average PPBS cycle time. The Funding Period and Fiscal Counter model the fiscal allocation of funds to the program. Actual spending becomes a function of total effective manpower costs (i.e. total contractors plus overtime). Note that the model explicitly capture overhead costs. These costs are included in the value of the contracting fee ($6597 per engineer per month).[156]

Funding shortfalls occur as two dynamics. First, a funding gap is created that is relieved by first order control through Change to Budget and subsequent flow through the fiscally controlled Program Budget Rate. The second effect is the temporary decrease in funding to contractors (i.e. release of contractors) and the increase of NAVSEA engineering efforts to compensate. As budget levels rise once more, these trends reverse. Should a funding surplus occur, the dynamic is reversed: the budget decreases over time and the program assigns increasing levels of contractors to consume the surplus.

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[155] Naval Sea Systems Command, Ship Design Project Histories: Volume II 1980-1989, estimated edit date June 1984, page 2.8.
[156] Ibid. FY1996 dollars projected from 1985 engineering cost estimates for contractors.

The final element of the model is the explicit modeling of contract types. Within the contracting environment, program managers have the option of awarding new Requests for Proposals (RFPs) or using existing contracts through other program offices. There are advantages and disadvantages to each. New awards provide the manager (PM) with a dedicated contract, tailored to the current program with no overhead costs imposed by external authorities. However, the RFP process can take as long as 18 months to establish and begin actual design work. For this reason the PM may offer to fund an existing contract being managed by a NAVSEA directorate or other program office. Such an approach offers rapid access to contractors and design resources. However, the managing office imposes an overhead charge of 10% or more of the design costs. Additionally, the contract may not be tailored to the particular design problem being studied. As such, the PM must decide on an appropriate policy for allocation of contract types. In the model, these allocations are fixed as percentages of contractor assignment. The percentages transition to RFPs as the process matures.

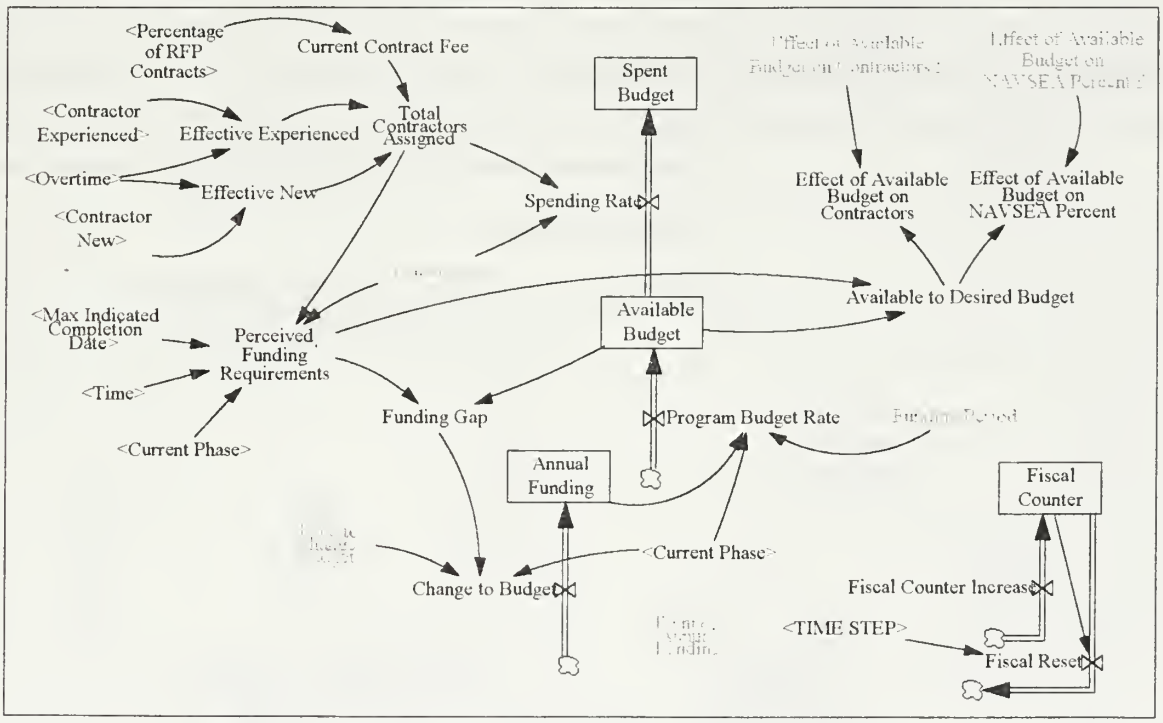

Figure 54 Naval Ship Design Process Model Financial Sector

6 *Hypothesis Testing, Modeling Results and Conclusions*

6.1 Baseline Model Results

The desired behavior for the baseline model is to match the levels and dynamics of the DDG-51 program. Obtaining specific data for such an effort is difficult. As was noted in the DAC study, program management statistics are highly variable in quality and availability, particularly with respect to manpower efforts. Specific documents with such information have been published. These include several NAVSEA documents: the DDG-51 Guided Missile Destroyer Preliminary Design History, the Contract Design History for the Guided Missile Destroyer (DDG 51 Class), and the Ship Design Project Histories: Volume I, II and III. From these documents, manpower and budgetary trends can be extrapolated. Figure 55 illustrates the NAVSEA effort for several recent design programs. Strategically, NAVSEA has reduced (over time from FFG-7 to CG-47 to DDG-51) the numbers of government personnel assigned to the program. Operationally, the graph demonstrates increasing engineering efforts through each design phase with several dynamic rises midway through each program, declines at the end of a phase, and an extended level of decrease at the end of contract design.

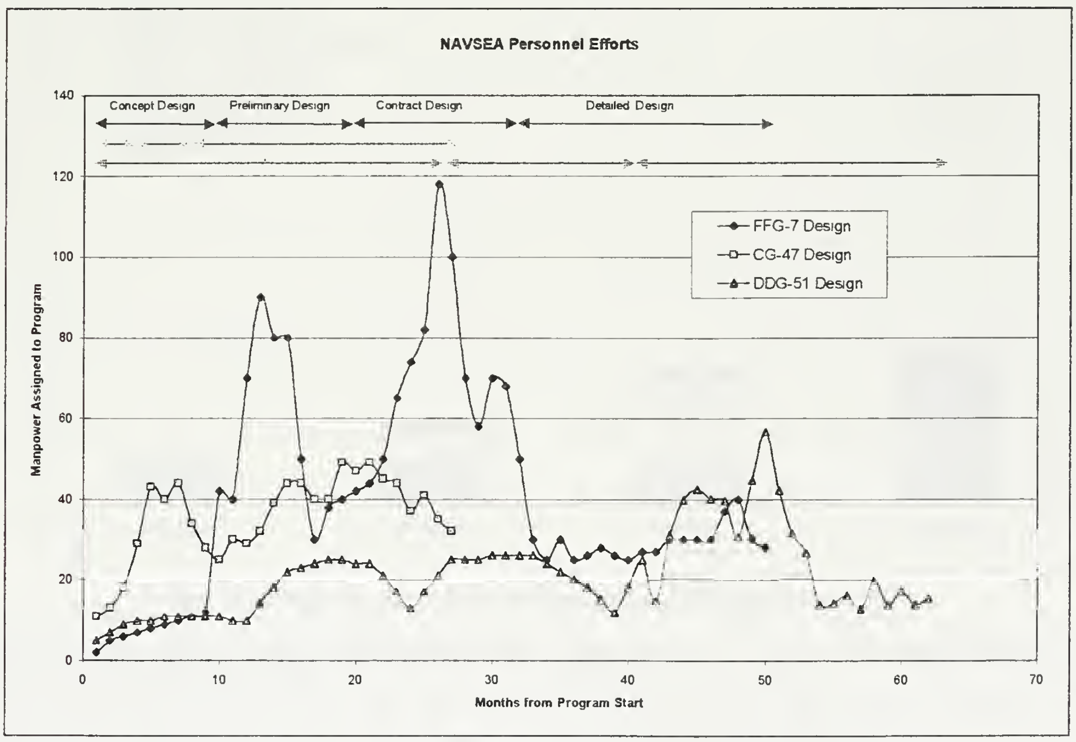

Figure 55 Early Phase NAVSEA Personnel Effort for Surface Combatant Design Programs[157]

Figure 43 shows the significant difference in numbers of government and contractor personnel. The NAVSEA effort is small compared to that of Other Government Agencies (OGA) and contractors. Generally, the trend for each category of personnel follows the total trend effort for the program. There are some unusual

variations in contractor and OGA effort. However, as each of these types require budget expenditures to acquire. The variations represent a choice by the program manager to select one type of contractor over the other.

Another noteworthy dynamic is the transition between design disciplines over the course of the project. Recall the design disciplines and design products discussed in Chapter 4. Consider the trends shown in Figure 56. In early stages of design, programmatic interfaces dominate along with a significant effort in system performance assessment. Other engineering efforts provide input to these categories, but the delivered products are substantially less. This reflects the early goal of design to determine requirements and needs. As the program matures, increasing effort is in high risk design categories such as combat systems and marine systems integration. In the final stages of the design process, very specific efforts in component level definition (hull structural drawings, arrangements drawings, machinery arrangements, MELs and parts lists) dominate the engineering effort.

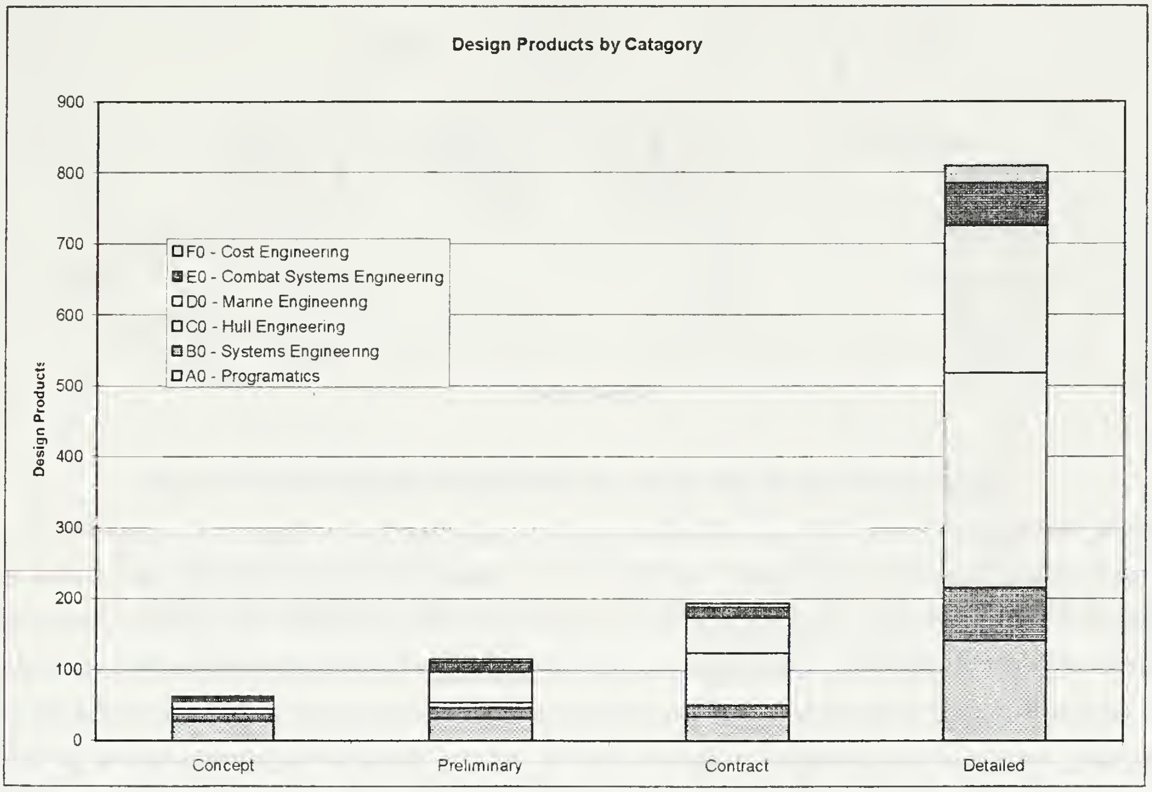

Figure 56 Design Product Trends (Number of Total Deliverables)[158]

Based on these trends and the dynamics discussed in Chapters 4 and 5, the naval ship design process model was adjusted to match the baseline behavior of the DDG-51 program. Figure 57 shows the model results for total assigned manpower compared to the DDG-51 program. The model results were calibrated once by adjusting the nominal productivity rates (Adjust Rate, see Figure 42) to match project duration to the DDG-51. These results demonstrate the effectiveness of the dynamic model to capture the dynamic behavior of a complex process.

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[157] Data is complied from documentation listed in Chapter 8.4.
[158] Ibid.

Although not all levels are captured precisely, the dynamic events are. Note the agreement of the model and data from months 35 to 45 and from months 50 to 90.

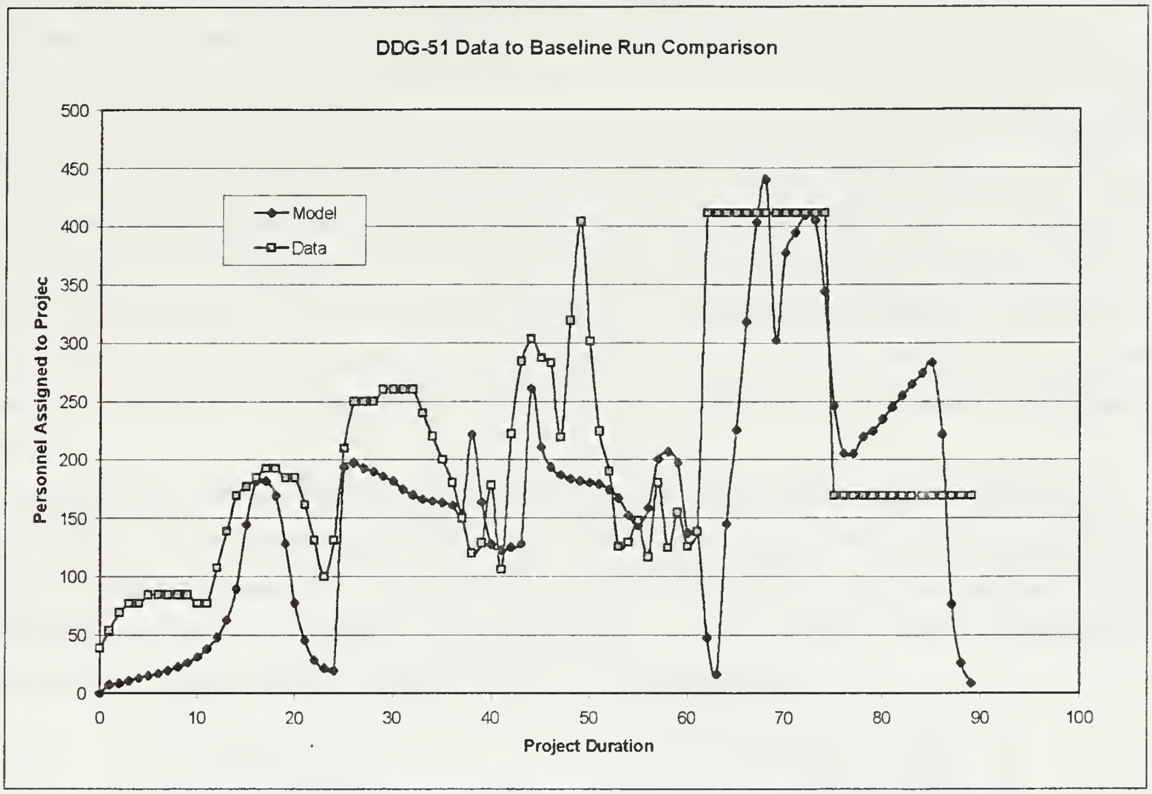

Figure 57 Initial Baseline Results from the Naval Ship Design Process Model

The differences between the model and data may be accounted for in several ways. First, note that the data shows initial manpower levels of over 50 personnel. This is deceiving. The program had actually started concept studies as early as 1978. The model starts from 0 personnel in 1980 (milestone 0 for the program). Another issue with the data is that it implies all personnel assigned to the project are working on the project 100% of the month. In reality, NAVSEA personnel and contractors on existing contracts may have worked only a fraction of the time on the DDG-51 and the remaining time on other projects. As such, the data overestimates manning levels…particularly in early design phases. Finally, the model was only calibrated using a single variable. Given more time and resources, the model could be calibrated more accurately using sensitivity analysis of all model constants and through further refinements of the model behaviors.

These minor issues do not detract from the value of the results. The model does capture the process dynamics. This alone is worthwhile as it provides insight into the causes of specific process behaviors. For instance, the oscillations at month 45 and month 57 correlate to the end of fiscal cycles where funding shortfalls occurred. Armed with this prediction, a program manager may be able to negotiate a budget increase to prevent future oscillations and subsequent schedule shifts. Thus, the model provides useful results and can be used effectively to assess specific hypotheses.

6.2 What if CAE/CAD/CAM Are Used?

The first hypothesis examined with the model is how the application of computer based design tools effects the process dynamics, manpower loading and duration. In earlier chapters, some specific dynamic impacts of computer aided engineering, design and manufacturing (CAE/CAD/CAM) were addressed. Computer based design reduces error rates by allowing automated interference checking and QA of design products. Several shipbuilders (BIW, Newport News Shipbuilding) have reported these improvements. However, reduced errors rates have not come without serious growing pains. At BIW, the use of early versions of CAD resulted in very high false error rates, a false error being the designation of an interference or blockage in the CAD model when no such problem exists. From 1991 through 1997, the engineering division used 3 revisions of the CAD software, with false error rates per zone per design review decreasing from an average of 1000 in 1991 to 100 in 1994 to 10 or less in 1997. Although these rates reflect exponential improvements, the five years of learning and adjustment were difficult to justify.[159]

Other organizations have claimed substantial reductions in design time with CAD system usage. The Daewoo Shipyard of Korea installed a CAD system to perform structural design. Table 42 shows the trends in usage of that system at Daewoo. From the data, it is quite apparent that the organization was committed to CAD modernization. The number of computers was increased while the number of designers and the design duration were reduced. Could these results be realized for the naval ship design process?

Item	'89	'90	'92	'94
No. of Workstations	10	40	60	82
No. of Designers (No. using Workstations)	190 (20)	156 (90)	156 (110)	164 (118)
Computerized Drawings (%)	26	50	92	96
Detailed Design Period (months)	7.5	7.0	6.0	5.5

Table 42 Performance Status of Steerbear-Hull Design System at Daewoo Shipbuilding[160]

Suppose a specific CAE/CAD/CAM system is proposed. Such a system provides an integrated design and data management environment for the design process. Based on the Daewoo experience, system designers advertise the following attributes for the system::

- Error rate is reduced by 50% (computer integration and design automation should reduce errors)
- Error discovery is increased by 50% (CAD software provides explicit interference detection)
- Experience (learning) time is increased to 6 months[161] (computer systems do require time for training and familiarization)
- Coordination rate is 50% faster (data transfer ranges from instantaneous with a product model to improved with email).

[159] David Hinds, interview at Bath Iron Works, Brunswick, ME, November 15, 1997.
[160] Chris Kennison, KCS Users Meeting Minutes, Kockums Computer Systems, Annapolis, MD, October 31, 1997.
[161] David Hinds, interview at Bath Iron Works, Brunswick, ME, November 15, 1997.

Based on these properties, a model run is developed. The results are shown compared to the baseline run in Figure 58. The result of these changes is a 13 month reduction in the total design process. This is consistent with the results seen for Daewoo Shipbuilding. Some dynamics are particularly noteworthy. The concept design process does not appear to change. The preliminary design process begins slightly earlier, but really takes off over the baseline case by month 30. Specifically, the design interactions are improved by faster coordination and reduced errors. Thus, more tasks are available for final iteration in preliminary design at an earlier point. The contract design starts 5 months earlier and detailed design is able to start 8 months earlier. Thus, the application of computer design, applied to a few specific variables (error rates, learning and coordination) provides over a one-year cycle time reduction. Note, however, that the process did not reduce the number of personnel and even increased manpower levels in early stages.

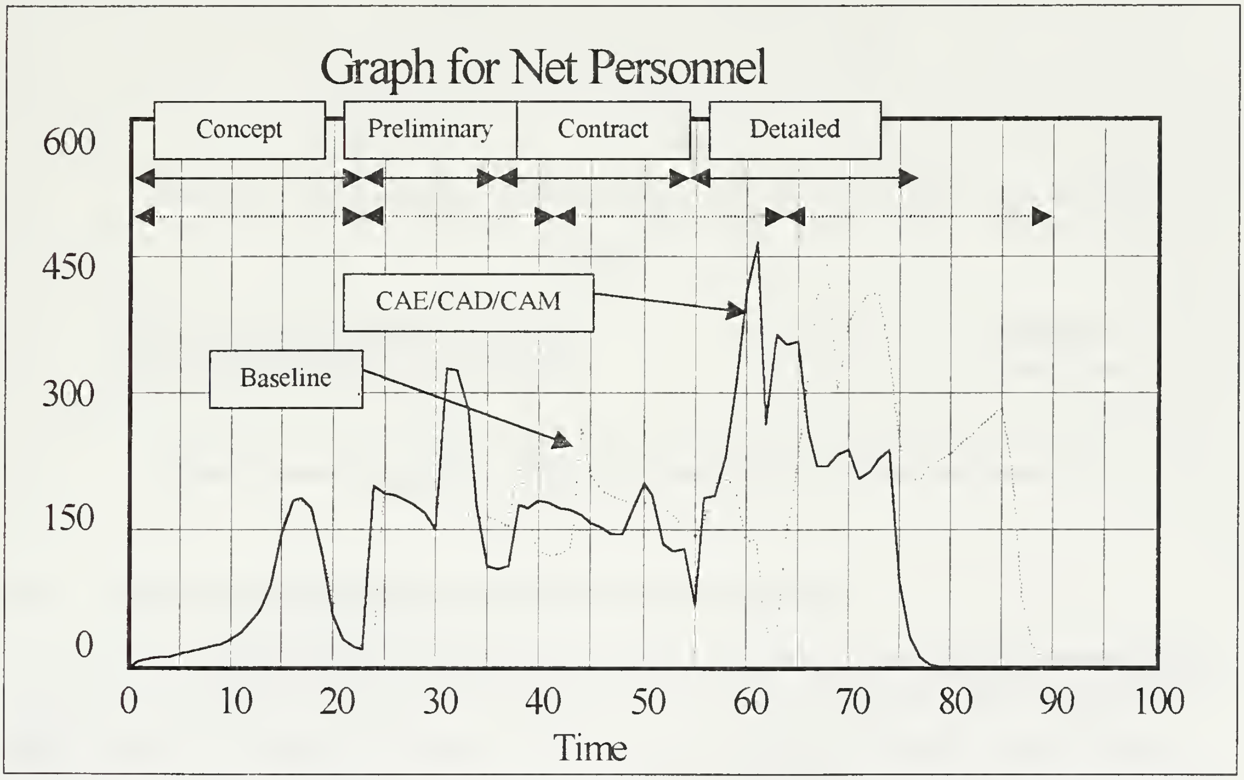

Figure 58 Comparison of Baseline Model to CAE/CAD/CAM Hypothesis

What if the advertised improvements are not fully realized? Such a circumstance is consistent with the implementation difficulties described previously for BIW. Specifically, suppose the error rate from baseline methods is only reduced by 25% vice 50%. The model results for this case are shown in Figure 59. The results demonstrate that the process duration is not sensitive to a change in error rate. However, the number of personnel required to maintain that schedule, particularly in contract and detailed design, is very sensitive with a 12% increase in personnel assigned over the project. As a result, manpower costs increase by over $30 million due to the unrealized potential of the CAD system.

This example indicates the power of system dynamics modeling to analyze schedule risks associated with process improvements.

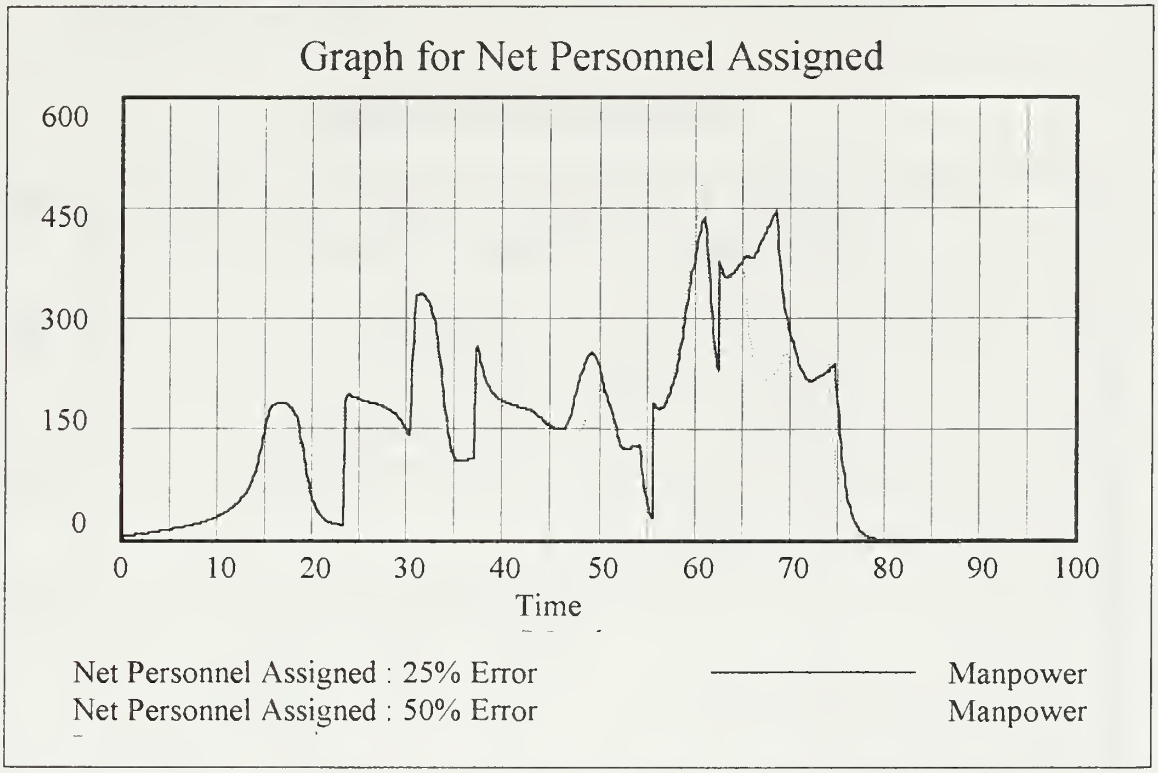

Figure 59 Sensitivity of CAE/CAD/CAM Hypothesis to Error Rate Improvements

6.3 What if Concurrent Engineering and IPTs Are Applied

Concurrent Engineering and IPTs are proposed as methods to improve responsiveness of the design process. Previous discussions examined some specific dynamic impacts of concurrent engineering, IPTs, and IPPD. The ability of engineers to effectively communicate with one another should reduce the number of design iterations required for convergence. Additionally, concurrent engineering front loads many design tasks earlier in the process such as producibility.

For this case, suppose process improvements are advertised to provide the following process modifications:

- Error discovery increased by 25% (teaming will provide continuous data exposure to multiple designers and disciplines)
- Coordination rate is 100% slower (due to communication overhead costs)
- Design feedback is reduced by 50% (teaming provides better knowledge among designers of task interaction impacts and communication of data trends)

- Approval and Review periods are reduced by 50% (teaming can provide interim communication of design requirements, attributes and effectiveness throughout the process rather than during specific approval and review periods).

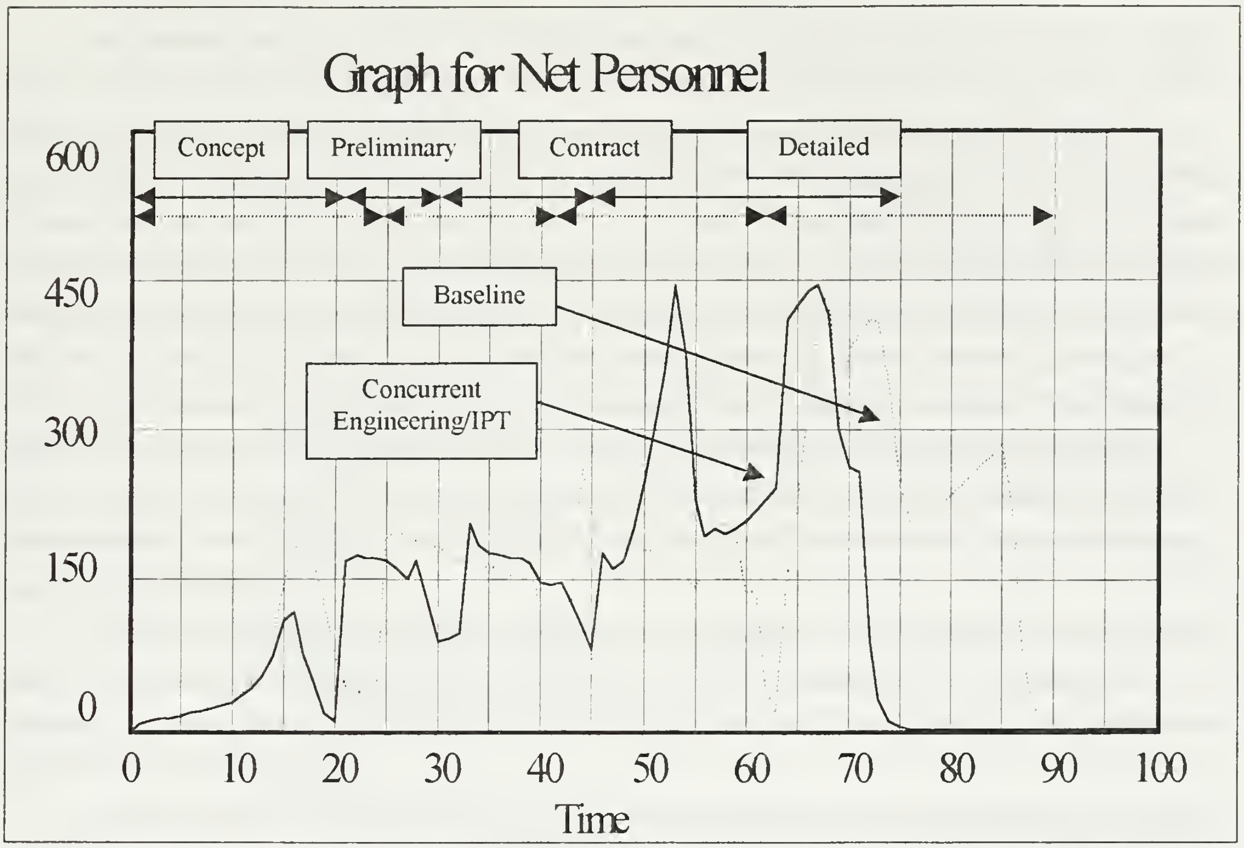

Figure 60 Comparison of Baseline Model to Concurrent Engineering/IPT Hypothesis

Applying these process modifications to the model provides results as shown in Figure 60. These results show a 16 month reduction in the total design process. Additionally, the net personnel assigned for the entire project (integration of the graphs) is decreased by 10%. This is an expected benefit from the use of cross-disciplinary design teams. Some of the dynamics are particularly interesting. All the design phases occur faster and with fewer personnel. The faster design periods allow the process to better weather budget transitions by compacting the design phases (preliminary and contract design) into periods of about 12 months each. The preliminary design process begins slightly earlier, but really takes off over the baseline case by month 30. Finally, the lead ship design occurs so much more quickly that the manufacturing design is actually delayed (represented by the saddle in the curve) to await the JIT pull from production. Generally, we can conclude that the application of teaming in design process, as applied to a few specific variables (error rates, design feedback, approval schedules, and coordination) provides almost a one-and-a-half-year cycle time reduction and overall manpower reductions.

As with the CAE/CAD/CAM example, sensitivity analysis provides insight for risks to program performance. In this example, suppose design feedback is only reduced by 40% vice 50%. Such a circumstance would occur if design requirements were continually changing such as during the end of the Cold War. The result is a lengthening of the design process by 3 months, a 4% increase in manpower costs and an increased requirement for personnel during concept design. Again, sensitivity provides the program manager with a tool to assess the expected impacts and risks of proposed process improvements.

7 *Conclusions and Future Work*

7.1 Conclusions

Most schedule analysis tools (PERT, CPM, DSM) only provide the ability to capture hard process variables such as design concurrence or phase durations. These operationally and statistically based methods fail to capture the dominant dynamic influences (human factors, error propagation and design feedback) that ultimately lead to schedule growth. Additionally these methods do not accurately reflect non-linear impacts such as overtime, fatigue, schedule pressures and learning curves (see Chapter 1.1.1). For these reasons, the naval ship design process model is necessary and useful. System dynamics modeling provides one of the few means to assess process improvements that must incorporate not only architectural changes to the process, but the responses of real people to those changes. The obvious physical relationships of naval architecture, marine engineering, combat systems engineering and systems engineering are explicitly modeled. Cost constraints and policy reactions are captured. These impacts are captured in many other system dynamics models as well (see Tan and Bligh, 1998 and Rodrigues and Bowers, 1995.) However, these models do not capture the issues of multi-functional design, design feedback or program policies unique to naval ship design. For this reason, the inclusion of the DSM structure in the naval ship design process model is necessary.

The naval ship design process model (see Chapter 8.7 for the baseline model) contains the necessary detail to capture the dynamics of a ship design program. Specifically, the DDG-51 program behavior is captured (see Chapter 6.1). As the DDG-51 program is now almost two decades old, not all baseline variables are appropriate for use with current design programs.

For instance, there is a trend to shift greater levels of system analysis into concept design and to more fully develop the concept variants presented for AoA consideration. By this trend, concept design in the 1990's increasingly examines details reserved for preliminary design in the 1980's. To accommodate this trend, model variables for initial tasks levels must increase in the concept design phase to reflect the increased design analysis. Additionally, the introduction of integrated design environments increases productivity relative to specific design tasks. This is reflected in the trends shown previously in Table 42. However, as the level of analysis increases more rapidly than productivity, the resultant design rate may actually decrease. Such specific modifications to variables are necessary to assess modern programs with the naval ship design model.

Despite the need for changing variables, the generic structure of the naval ship design model (see Chapter 5) is accurate and does reflect the policy and process mechanisms contained in the ship design process. Thus, with modifications of variables consistent with current design process trends (see discussions in Chapters 4.4 through 4.9) and calibration of those variables, the model is applicable to ship design programs like the DD-21 or CVX.

Further, the baseline model provides a structure to judge the impacts of potential process improvements and the risks associated with the assumptions of those improvements. As demonstrated in Chapters 6.2 and 6.3, gains in cycle time and manpower reduction are sensitive to the assumptions of the proposed improvements. Program managers can test assumptions and design the process organization to optimize schedule performance. Additionally,

the program manager can use the model to trade-off cycle time against mission effectiveness and cost as determined by their respective analysis methods (see Chapters 1.1.2 and 1.1.3).

7.2 Future Uses and Work

The naval ship design process dynamic model has three potential future uses:

1. Testing of specific management policies and process improvements
2. Understanding of the behavioral forces at work in a process
3. Prediction of future trends

For policy testing, the model provides a means to test and optimize a management plan (such as when to allow schedule shift or what fraction of NAVSEA personnel to involve in a project.) However, a note of caution is necessary. The full use of any model for policy implementation must be contingent on the support of all process participants. Specifically, if knowledgeable personnel have not reviewed the model's structure and behavior, it implementation will be flawed (i.e. the dynamics are correct but the model structure is not tangible or operationally accurate.) The result would be accurate baseline behavior but inaccurate hypotheses. As such, continuous comparison of the model with observed results must take place. It is in this manner that the model can provide understanding of behavior forces.

The model can also be studied to reveal behavior forces within the design process. Through constant dialog, process participants and modelers can begin to recognize the causes of cycle time growth, the dynamics of undiscovered errors, the effects of personnel changes on the process, and a multitude of other process behaviors. As managers change their mental models of the process to reflect more accurately the dynamic impacts of their management decisions, process improvements can be better implemented. Additionally, process authorities are better armed with tools to address critics and combat constraining externalities.

Armed with accurate models and understanding of those models, process managers can begin to predict and gauge the future trends of process improvements. As demonstrated in Chapter 6, initial results for improvements such as IPTs and SBD have the potential to significantly reduce cycle time. The next step is the calibration of the model to a current program (such as DD-21) and monitoring the expected results against observation. In this manner, a program manager has the necessary metrics to modify management policies before critical thresholds (spiraling cost or schedule growth) are reached.

Future modeling work to support and implement the above listed uses include:

1) Discuss the model with program participants. Calibrate and validate critical dynamics such as cost impacts, scheduling methods and manpower allocation.
2) Integrate the model with other dynamic models (McCue, 1997) for analysis across design and production. The naval ship design process model may ultimately be incorporated in a life cycle process analysis.
3) Develop dynamic models for externalities (arms race dynamic, etc) and incorporate these dynamics endogenously to the model.
4) Refine the model to
    a) improve manpower allocations for task coordination and QA.

b) improve Program Planning Budgeting System (PPBS) components relative to cost

5) Obtain improved baseline, comparative data by

   a) examining additional metrics (other than manpower levels) at concept and preliminary design to reduce the inaccuracies of collected data

   b) examining dynamic fluctuations of detailed design manpower levels from shipyards and SUPSHIP offices

6) Perform dedicated case studies to analyze hypotheses such as

   a) the impact of shifting design transition from government to industry earlier in the process

   b) the dynamic impacts of scope growth in an open architecture design

These model improvements will provide greater fidelity and usefulness of the model for future use in assessing the system optimization and dynamics of the naval ship design process.

8 *Appendices*

8.1 Bibliography

Abdel-Hamid & Madnick, Software Project Dynamics: an Integrated Approach, Prentice Hall, New Jersey, 1991.

Alfeld and Shepard, "SNAP-Simulating New Acquisition Processes", CAIV Workshop, Decision Dynamics INC, 11-12 July 1997.

Alfeld, Wilkins and Pilliod, "The Virtual Shipyard: A Simulation Model of the Shipbuilding Process", The Society of Naval Architects and Marine Engineers, April 21-23, 1997.

Allan Andrew, "Multi-Attribute Decision Making Analysis with Evolutionary Programming Applied to Large Scale Vehicle II", Thesis for Ocean Engineering, Massachusetts Institute of Technology, Cambridge, MA, May 1998.

Andy Summers, , DDG 51 Guided Missile Destroyer Preliminary Design History, Naval Sea Systems Command, June 1984.

Andy Summers, DDG 51 Guided Missile Destroyer Contract Design History, Naval Sea Systems Command, June 1987.

Baum and Ramakrishnan, "Applying 3D Product modeling Technology to Shipbuilding", Marine Technology, January 1997.

Brown and Welsh, MIT Math Model – FFX, Massachusetts Institute of Technology course 13.412, fall 1996.

C. R. Lloyd, "Design Process for the AEGIS Destroyer Program", Presentation, Bath Iron Works D87 Class Design Office, November 18, 1997.

Chris Kennison, KCS Users Meeting Minutes, Kockums Computer Systems, Annapolis, MD, October 31, 1997.

Colton and Company, http://www.coltoncompany.com, Arlington, VA.

Construction Industry Institute, "Quantitative Effects of Project Change", CII Source Document, March 1990.

Crane, Eda, Landsburg, "Controllability", Principles of Naval Architecture, Society of Naval Architects and Marine Engineers, Jersey City, NJ, 1988.

David Brown, "Naval Architecture", Naval Engineers Journal, January 1993.

Defense Acquisition Deskbook Joint Program Office, "Defense Acquisition Deskbook, Version 2.2.87", Wright-Patterson Airforce Base, Dayton, OH, December 15, 1997.

Defense Systems Management College, The Program Manager's Notebook, Fort Belvoir, VA, June 1993.

Dr. Louis Alfeld, "The System Dynamics Modeling Methodology", Decision Dynamics Inc, 1994, www.decisiondynamics.com.

Dr. Paul Kaminski, Under Secretary of Defense (Acquisition and Technology), interview in Program Manager, January-February 1997.

Eppinger, Whitney, Smith and Gebala, "A Model-Based Method for Organizing Tasks in Product Development", Working Paper, Massachusetts Institute of Technology, 1993.

Fireman, Fowler, McIntire and Wilkins, "LPD 17: In the Midst of Reform", Naval Engineers Journal, May 1995.

Ford and Sterman, "Dynamic Modeling of Product Development Processes", Sloan School of Management, Cambridge, MA, February 1997.

Gale and Scott, "Early Stage Ship Design Seminar", Society of Naval Architects and Marine Engineers, October 1995.

Hope and Stortz, "Warships and Cost Constraints", Naval Engineers Journal, March 1986.

Hughes, Ship Structural Design, Society of Naval Architects and Marine Engineers, Jersey City, NJ, 1988.

J. Evans, "Basic Design Concepts", Naval Engineers Journal, November 1959.

James Lyneis, "Calibration of System Dynamic Models", a presentation to MIT-Sloan course Application of System Dynamics, Cambridge, MA, April 17, 1998.

Jay W. Forrester, "The Beginning of System Dynamics", banquet talk at the international meeting of the System Dynamics Society, Stuttgart, Germany, July 13, 1989.

Jim Hines, "Molecules of Structure Version 1.3", LeapTec and Ventana Systems, 1997, page 85-86.

John Dalton, Implementation of Mandatory Procedures for Major and Non-Major Defense Acquisition Programs and Major and Non-Major Information Technology Acquisition Programs (SECNAVINST 5000.2B), Department of the Navy, Washington DC, December 6, 1996.

Jorgen Randers, "Guidelines for Model Conceptualization", Elements of System Dynamics Method, MIT Press, Cambridge, MA, 1980.

Keane and Tibbitts, "A Revolution in Warship Design: Navy-Industry Integrated Product Teams", Journal of Ship Production, November 1996.

Keane and Tibbitts, "Making Design Everybody's Job", Naval Engineers Journal, May 1995.

Keane and Tibbitts, "Naval Ship Design in the 21st Century", Society of Naval Architects and Marine Engineers, Jersey City, NJ, 1993.

Kenneth Cooper, Naval Ship Production: A Claim Settled and a Framework Built, Pugh-Roberts Associates, Cambridge, MA, December 6, 1980.

Kockler, Withers, Poodiack and Gierman, Systems Engineering Management Guide, Defense Systems Management College, January 1990.

MIT Course 13.64, "CVX Product and Process Planning", Massachusetts Institute of Technology, Cambridge, MA, Summer 1997.

Myles Hurwitz, "Leading Edge Advanced Prototyping for Ships (LEAPS): an Integrated Architecture for Early Stage Ship Concept Assessment Software", David Taylor Research Center, Bethesda, MD, 1997.

Myron Ricketts, Manual for Naval Surface Ship Design Technical Practices, Naval Sea Systems Command, Washington DC, 1980, Volume I-III.

Naval Sea Systems Command, Ship Design Project Histories: Volume I, II and III, Washington, DC, September 1978, May 1986 and August 1996.

Naval Surface Warfare Center Carderock Division, "Getting Started & Tutorials: Advanced Surface Ship Evaluation Tool (ASSET) Family of Ship Design Synthesis Programs", September 30, 1997.

Normal Hamlin, "Ship Geometry", Principles of Naval Architecture, Society of Naval Architects and Marine Engineers, Jersey City, NJ, 1988.

Paulling, "Strength of Ships", Principles of Naval Architecture, Society of Naval Architects and Marine Engineers, Jersey City, NJ, 1988.

Philip Sims, "Ship Impacts Studies", Naval Engineers Journal, May 1993.

Polini, Wooley, Butler, "Impact of Simulation-Based Design on Today's Shipbuilders", Marine Technology, January 1997.

RADM Roger B. Horne, "Concept to Commissioning, Improving the Ship Design, Acquisition and Construction Process: Strategic Plan", Naval Sea Systems Command, Washington, DC, June 1991.

RADM Roger B. Horne, "Concept to Commissioning: Ship Design, Acquisition and Construction Process Improvement Workshop II", Richmond, VA, May 6-7, 1991.

Richard de Neufville, Applied Systems Analysis: Engineering Planning and Technology Management, McGraw-Hill Inc, 1990.

Robert Kaplan, "Analog Devices: The Half-Life System", Harvard Business School case study, 1990.

Rodrigues and Bowers, "System Dynamics in project management: a comparative analysis with traditional methods", System Dynamics Review, Volume 12 number 2, Summer 1996.

Roger Horne, Improving the Ship Design, Acquisition and Construction Process: Strategic Plan, Naval Sea Systems Command, Washington DC, June 1991.

Ron Nix, "T-AG9X Preliminary/Contract Design Estimates", Naval Sea Systems Command, January 16, 1987.

Rost and Tighe, 1992 Shipyard Costs and Capabilities, Center for Naval Analysis, Alexandria, VA.

Roy Harrington, Marine Engineering, Society of Naval Architects and Marine Engineers, Jersey City, NJ, 1992.

Ryan and Jons, "Improving the Ship Design, Acquisition and Construction Process", Association of Scientists and Engineers, 28th Annual Technical Symposium, 11 April 1991.

Simmons, "Assessment of Options for Enhancing Surface Ship Acquisition", Institute for Defense Analyses, March 1996.

Storch, Hammon, Bunch and Moore, Ship Production, Society of Naval Architects and Marine Engineers, Jersey City, NJ, 1995.

Tan and Bligh, "A New Approach to an Integrated CAD Method for Surface Ship Design", Naval Engineers Journal, January 1998.

Timothy McCue, "The Dynamics of Naval Shipbuilding-a Systems Approach", Thesis for Massachusetts Institute of Technology, June 1997.

Towles, Rocholl, Jeffers and Platt, "Force Affordability Modeling: the Dynamic Investment Balance Simulation (DIBS)", presentation to Naval Surface Warfare Center Carderock Division, Bethesda, MD, April 15, 1997.

Towles, Rocholl, Jones, Jeffers and Platt, "System Wormhole Analysis Tool (SWAT): a Simulation Based Acquisition Initiative," presentation to Naval Surface Warfare Center Carderock Division, Bethesda, MD, October 27, 1997.

Verne Stortz, "DDG-51 Cost Estimate Log", Naval Surface Warfare Center Carderock Division, Bethesda, MD, October 1984.

Vernon E. Stortz, "DDG-51 Design-Cost Trend Log", unpublished, Naval Surface Warfare Center Carderock Division, Bethesda, MD, August 1984.

Whatmore and Wintersteen, "A Review of Extant Design Tool Capabilities to Identify Common Design Tool for Future Collaboration", Naval Surface Warfare Center Carderock Division, Bethesda, MD, February 28, 1997.

Wilkins, Kraine and Thompson, "Evaluating the Producibility of Ship Design Alternatives", Journal of Ship Production, August 1993.

William Ball, "DoD Acquisition Policy and the Effect on Naval Ship Design", Society of Naval Architecture and Marine Engineering, February 25, 1992.

William S. Cohen, Report of the Quadrennial Defense Review, United State Department of Defense, May 1997.

8.2 Thank you…

I would like to extend my personal thank you to the following individuals who provided both much appreciated resource materials and valuable insights through discussions and interviews about the Naval Ship Design Process:

- CAPT Alan Brown (USN Ret), Massachusetts Institute of Technology
- CAPT Dennis Mahoney (USN), Massachusetts Institute of Technology
- CDR (Sel) Mark Welsh (USN), Massachusetts Institute of Technology
- Prof. Hank Marcus, Massachusetts Institute of Technology
- Prof. Nelson Repenning, Sloan School of Management
- CAPT Barry Tibbitts (USN Ret), John J McMullen Assoc.
- Christopher (Kit) Ryan, Naval Sea Systems Command
- CAPT Charles Calvano (USN Ret), Navy Post Graduate School
- ADM Mark Palcaz (USN Ret), Newport News Shipbuilding
- ADM Wayne Myers (USN Ret), Techmatics Inc.
- Ron Kiss, SYNTEK Inc
- Reuven Leopold, SYNTEK Inc.
- John Leadmon, Naval Sea Systems Command
- Bob Keane, Naval Surface Warfare Center Carderock Division
- Dr. Lou Alfeld, Decision Dynamics Incorporated
- William Shepard, Decision Dynamics Incorporated
- Joe Daley, Gibbs & Cox Assoc.
- Ron Nix, Naval Sea Systems Command
- Philip Sims, Naval Sea Systems Command
- Diane Burton, Naval Sea Systems Command
- Don Cebulski, Naval Sea Systems Command
- Todd Cary, Naval Sea Systems Command
- Jeff Hough, Naval Sea Systems Command
- James Mays, Naval Sea Systems Command
- Mark Henry, Naval Sea Systems Command
- LCDR Greg Thomas (USN), Naval Sea Systems Command
- CDR Steven Petri (USN), Naval Surface Warfare Center Carderock Division
- Marc Greenburg, Naval Surface Warfare Center Carderock Division
- Miles Hurwitz, Naval Surface Warfare Center Carderock Division
- Mike Jeffers, Naval Surface Warfare Center Carderock Division
- John Trumble, Naval Surface Warfare Center Carderock Division
- Richard Van Eseltine, Naval Surface Warfare Center Carderock Division
- Bruce Wintersteen, Naval Surface Warfare Center Carderock Division
- Thomas Conrad, Naval Undersea Warfare Center Newport
- Rother Hodges, Naval Undersea Warfare Center Newport
- Scott Ripley, Newport News Shipbuilding
- CDR Joe Berner (USN), PMS 500
- Jim Lyneis, Pugh Roberts and Associates
- Prof. David Ford, University of Bergen
- Prof. Tom Lamb, University of Michigan
- LT Tim McCue, Supervisor of Shipbuilding San Diego
- Matt Tedesco, National Steel and Shipbuilding Corporation
- Eric Suehrstedt, Bath Iron Works
- David Hinds, Bath Iron Works

8.3 Glossary and Abbreviations

3-D Product Model - Captures all of the information needed to describe a ship

AoA – Analysis of Alternatives, an analysis of the costs and operational effectiveness of alternative material systems to meet a mission need and the associated program for acquiring each alternative.

ASR - Alternative System Review

ASR – Acquisition Strategy Report, describes the acquisition approach to include streamlining, sources, competition and contract types throughout the period from beginning of Phase I, through end of production. An annex to the IPS.

Architecture - A structure that shows the elements and their relationship for a set of requirements or a system concept or both.

ATC - Affordability through Commonality Program

BIW - Bath Iron Works

CALS-GCO (Continuous Acquisition and Life Cycle Support- Government Concept of Operations): A document. Provides the Government Concept of Operations (GCO) for data associated with the SC 21 Program in conformance with the basic strategy of Continuous Acquisition and Life-Cycle Support (CALS).

CDR - Critical Design Review, review conducted to determine that the detailed design satisfies performance and engineering requirements of the development specification; to establish the detailed design compatibility among the item and other items of equipment, facilities, computer programs, and personnel; assesses producibility and risk areas; and to review the preliminary product specifications.

CDRL – Contract Data Requirements List. Document used to order and require delivery of data. Tells contractor what data to deliver, when and how it will be accepted, where to look for instructions, etc.

COEA – Cost and Operational Effectiveness Analysis, OBSOLETE, superceded by AoA.

Concurrent Engineering – A systematic approach to the integrated, concurrent design of products and their related processes, including manufacture and support. This approach is intended to cause developers, from the beginning, to consider all elements of the system life cycle from requirements development through disposal, including cost, schedule and performance.

Configuration item - An item that satisfies a documented set of requirements and is designated for separate configuration management to include any item required for logistic support or designated for separate procurement.

Configuration management - For configuration items, (1) the identification and documentation of the configuration, (2) the control of changes to the items or their documentation, (3) configuration status accounting, and (4) the auditing to confirm that conformance to all requirements has been verified.

Cost As an Independent Variable - Methodologies to acquire and operate affordable DOD systems by setting aggressive, achievable cost objectives and managing achievement of these objectives. Cost objectives shall

be set to balance mission needs with projected out-year resources, taking into account anticipated process improvements in both DOD and defense industries.

COTS - Commercial off the Shelf

CPM - Critical Path Method

CVX - Next generation aircraft carrier

DAB – Defense Acquisition Board, the senior DOD acquisition review board chaired by the Under Secretary of Defense for Acquisition. The Vice Chairman of the Joint Chiefs of Staff is the Vice-Chair. Other members include the Deputy USD(Acquisition), Acquisition Executives of the armed services; the Director of Defense Research and Engineering; the Assistant Secretary of Defense for Program Analysis and Evaluation; and the Comptroller of the DOD.

DARC – Defense Acquisition Regulatory Council, one of two councils authorized to generate changes to the Federal Acquisition Regulation (FAR). DARC members are from the Office of the Under Secretary of Defense for Acquisition, the DOD components and NASA.

DCP – Decision Coordinating Paper, OBSOLETE, superceded by IPS.

DD-21 - Next combatant ship program after DDG-51, also designated SC-21.

DDG-51 Flight IIA - Added helicopter support and lengthened base design

Defense Acquisition Executive Summary (DAES) – summary report of program progress presented to Office of Secretary of Defense (OSD) for review.

Design - *noun*: The result of designing.

Design - *verb:* Architecting and selecting products (including processes) and corresponding personnel manpower, skill levels, and specialized training that satisfy all requirements and describing them so that the products can be manufactured or coded, verified, deployed, operated, supported, and disposed of and so that the personnel can be selected and trained.

DMRS - Defense Mobility Requirements Study

DoD Directive 5000.1 (March 15, 1996) - States policies and principles for all DoD acquisition programs and identifies the Department's key acquisition officials and forums, with supporting documents (DoD 5000.2-R) it provides mandatory procedures for major defense acquisition programs and major automated information system.

DT&E – Development Test and Evaluation, T&E conducted to measure progress, usually of components/subsystems, and to assist the engineering design and development process and verify attainment of technical performance specifications and objectives. Usually conducted under controlled or laboratory conditions. Can be conducted before or after production begins.

DWL - Designed Water Line

DYNAMO - System Dynamics modeling software

Engineering Change Proposal (ECP) - a proposal to the responsible authority recommending that a change to an original item of equipment be considered, and the design or engineering change be incorporated into the article to modify, add to, delete or supersede original parts.

Federal Acquisition Reform Act (FARA) - cited as the Federal Acquisition Reform Act of 1995, requires government construction projects to follow a two phase contracting approach; phase 1 will define technical requirements, approaches and evaluation procedures (but not detailed design specifications or cost ceilings) for open contract competition; phase 2 will award a contract based on the evaluation procedures delineated in phase 1.

Federal Acquisition Streamlining Act (FASA) - cited as the "Federal Acquisition Streamlining Act of 1994", the act allows government agents to negotiate limited contracts (by amount, duration and scope) without the requirements of open competition and contract bidding.

Functional Configuration Audit (FCA) - the formal examination of functional characteristics test data for configuration item, prior to acceptance, to verify that the item has achieved the performance specified in its functional or allocated configuration identification.

Functional analysis and allocation - The decomposition of each of the top-level functions to sub-functions to the point that each sub-function can be related to the elements of a physical hierarchy, the allocation of the top-level performance requirements and design constraints to the functions and sub-functions, and the capture of the aggregation in a functional architecture.

Functional architecture - The hierarchical arrangement of functions and their decomposition to sub-functions and the allocation of the top level performance requirements and design constraints to functions and sub-functions.

Functional baseline - The initially approved documentation describing a system's top level functional and performance requirements and design constraints and all changes thereto. The functional baseline can be changed only with Government approval. The functional baseline is usually initially approved near the end of the Program Definition and Risk Reduction Phase, as part of the procurement process for Engineering and Manufacturing Development.

Hull, Mechanical & Electrical (HM&E) – The totality of non-payload (typically combat systems) ship systems and components.

HVAC - Heating, Ventilation and Air Conditioning

Integrated Logistics Support (ILS) - A disciplined, unified, and iterative approach to the management and technical activities necessary to (1) integrate support considerations into system and component design; (2) develop support requirements that are consistently related to readiness objectives, to design, and to each other; (3) acquire the required support; and (4) provide the required support during the operational phase at minimum cost.

Integrated Management Plan (IMP) - A contractual description of the applicable documents, significant accomplishments, accomplishment criteria, events, and critical processes necessary to satisfy all contract requirements. The completion of each significant accomplishment is determined by measurable accomplishment criteria. The significant accomplishments have a logical relationship to each other and, in subsets, lead up to events. Each Event is, in turn, complete when the significant accomplishments leading up to it are complete. The critical processes are described by narratives that include Objectives, Governing Documentation, and an Approach. The IMP includes an indexing scheme (sometimes called a single

numbering system) that links each significant accomplishment to the associated CWBS element, event, significant accomplishment criteria, and tasks presented in the Integrated Master Schedule (IMS). The data in the IMP defines the necessary accomplishments for each event both for each IPT and for the contract as a whole.

Integrated Master Schedule (IMS) - The schedule showing the time (calendar) relationship between significant accomplishments, events, and the detailed tasks (or work packages) required to complete the contract. The IMS uses (and extends if necessary) the same indexing (or single numbering system) as used in the Integrated Master Plan (IMP).

Integrated Product and Process Development (IPPD) - A management technique that simultaneously integrates all essential acquisition activities through the use of multi-disciplinary Integrated Product or Process Teams (IPTs). Specifically defined in the DOD Guide to Integrated Product and Process Development, 5 Feb 96.

Integrated Product Team (IPT) - Team composed of specialists from all applicable functional disciplines working together (1) to deliver products and processes that affordably meet all requirements at acceptable risk and (2) to enable decision makers to make the right decisions at the right time by timely achievement of the significant accomplishments in the Integrated Master Plan (IMP).

IPS – Integrated Program Summary, a DOD Component document prepared and submitted to the milestone decision authority in support of Milestone I, II, III and IV reviews. It provides an independent assessment of a program's status and readiness to proceed into the next phase of the acquisition cycle.

Interface requirement - The functional and physical design constraints imposed on each other by two or more functions, items, or systems or between a system and a facility. Functional interfaces include signal, electrical, electromagnetic, and software. Physical interfaces include keep-out volumes and mating surfaces and connections.

Interface - The boundary, physical or conceptual, between two or more functions, systems, or items or between a system and a facility at which interface requirements are set.

IOC – Initial Operational Capability, the first attainment of the minimum capability to effectively employ a weapon, item or equipment, or system of approved specific characteristics, and which is manned or operated by an adequately trained, equipped, and supported military unit or force.

JIT - Just In Time, a "pull" system, driven by actual demand. Goal is to produce or provide one part just-in-time for the next operation. Reduces stock inventories, but leaves no room for schedule error. As much a managerial philosophy as it is an inventory system.

LBP - Length between Perpendiculars - usually the length of the ship at the waterline

Legacy system - A system/subsystem/component associated with or envisioned for a DOD application, that exists or can be anticipated to exist in a time frame that supports its inclusion as part of a design being developed to met a current requirement.

LFT&E – Live Fire Test & Evaluation, survivability testing and lethality testing required before full-scale production. Must be conducted (unless a waiver is approved by the USD(A)) on ACAT I and II programs for:

a. a covered system (a vehicle, weapons platform, or conventional weapon system designed to provide some degree of protection to the user in combat,

b. a major munitions or missile program or

c. a product improvement program that will significantly affect the survivability of a covered system.

Life Cycle Cost (LCC) - Life cycle costs include all Research and Development, Procurement, and Operation and Support costs from program inception to disposal of the last associated end item. The minimum categories of cost, which shall be used to estimate life cycle cost, are as follows:

Research and Development Costs: Includes all costs associated with conceptual/feasibility studies, basic research, advanced research and development, engineering design, fabrication and test of engineering prototype models (hardware), and associated documentation. These costs are generally non-recurring.

Procurement Costs: Includes all costs associated with the acquisition of systems/equipment (once the Research and Development has been completed). The following subcategories apply:

Construction Cost: Includes all facility construction, capital equipment and facility maintenance.

Manufacturing Cost: Includes all recurring and non-recurring costs associated with the production and test of multiple quantities of prime systems/equipment.

Non-Recurring Manufacturing Cost: Includes all fixed, non-recurring costs associated with the production and test of operational systems/equipment, such as manufacturing management, manufacturing engineering, initial factory tooling and test equipment, quality assurance, first article qualification test (reliability test, maintainability demonstration, support equipment compatibility, technical data verification, personnel test and evaluation, interchangeability, and environmental test) and related support, production sampling tests and related support.

Recurring Manufacturing Cost: Includes all recurring end item production costs such as fabrication, subassembly and assembly, material and inventory control, inspection and test, and packaging and shipping. Sustaining engineering support required on a recurring basis is also included.

Initial Logistics Support Costs: Includes operational test and support equipment, training equipment and spare/repair parts material costs.

Operation and Support Costs: Includes all costs associated with operating and maintaining the system after delivery. The following subcategories apply:

Mission Personnel: The costs of all pay and allowances for military personnel required operating the end item.

Unit Level Consumption: The cost of fuel, repair parts and supplies, depot-level repairables, training munitions and expendable stores, purchased services and the cost of temporarily assigned personnel.

Intermediate Maintenance: The cost of maintenance and repair actions performed by tenders and shore-based intermediate maintenance activities.

Depot Maintenance: The cost of ship overhauls and the installation costs of performing ship modifications (fleet modernization).

Sustaining Support: The cost of centrally provided material (equipment associated with ship modifications), sustaining engineering support, software maintenance and any other require sustaining support.

Indirect Support: The cost of system specific training, permanent change of station and medical care.

System Phase-Out and Disposal: The cost of condemning or disposing of an item.

LOA - Length over All - Total length of the ship

LSI - Lean Ship Initiative

Margin - Reserve for future growth

MARITECH - Marine Systems Technology

MILSPEC - Military Specifications

Molecules - System Dynamics Building Blocks generated by Jim Hines for Vensim and 15.875

NAVSEA - Naval Sea Systems Command

NAVSHPSSO - NAVSEA Shipbuilding Support Office

Non-Developmental Item (NDI) - Any item that is

(1) available in the commercial marketplace or

(2) previously developed and in use by a department or agency of the United States, a State or local Government, or a foreign Government with which the United States has a mutual defense cooperation agreement and that does not require unique upgrades or maintenance over its life-cycle to meet the current requirements.

In some cases NDI may be extended to include items that

(a) have been developed but are not yet available in the commercial marketplace or in use by a Government entity or

(b) require only minor modification or upgrade.

Open system: A system architecture which uses a generally accepted set of industry standards to define system interfaces such that components or subsystems can be readily substituted or upgraded.

Operating and support costs: see Life Cycle Cost

OT&E – Operational Test and Evaluation, the field test, under realistic conditions, of any item (or key component) or weapons, equipment, or munitions for the purpose of determining the effectiveness and suitability of the weapons, equipment, or munitions for use in combat by typical military users; and the evaluation of the results of such tests.

PCA – Physical Configuration Audit, physical examination to verify that the configuration item(s) "as built" conforms to the technical documentation which defines the item. Approval by the government program office of the CI product specification and satisfactory completion of this audit establishes the product baseline. May be conducted on first full production or fist LRIP item.

PDR - Preliminary Design Review, review conducted to ascertain if the preliminary design is to be committed to detailed design. Conducted for each configuration item to evaluate the progress, technical adequacy and risk resolution of the selected design approach, to determine its compatibility with performance and engineering

requirements of the development specification; and to establish the existence and compatibility of the physical and functional interfaces among the item and other items of equipment, facilities, computer programs and personnel.

PERT - Probabilistic Evaluation and Review Technique

Phase - Period of time that corresponds to one of the four primary phases of engineering and design. The phases include Concept Design Phase, Preliminary Design Phase, Contract Design Phase and Detailed Design Phase.

Physical architecture - The physical hierarchy and the functional requirements and design constraints for each element in the hierarchy. It can be viewed as an intermediate step between the functional architecture and the physical hierarchy, on the one hand, and the allocated baseline, on the other hand.

Procurement cost - see Life Cycle Cost

Product hierarchy, physical hierarchy - The hierarchical arrangement of products, processes, personnel skill levels, and manpower levels that satisfy the functional baseline. The top entry in the hierarchy is the system. The hierarchy extends to include all components and computer software units necessary to satisfy the functional baseline whether deliverable or not. It includes the prime operational hardware and software, Contractor-supplied support equipment, Government-inventory support equipment, technical manuals, training programs for both Government and Contractor personnel, Government personnel skill and manpower levels, spare parts requirements, and factory support equipment and tooling which collectively result in the system that satisfies the functional baseline.

PRR – Production Readiness Review, a formal examination of a program to determine if the design is ready for production, production engineering problems have been resolved, and the producer has accomplished adequate planning for the production phase.

PWBS - Product Work Breakdown Structure

QA - Quality Assurance

Requirements: Characteristics, attributes, or distinguishing features that a system or system element must have within a stated environment or set of conditions in order to meet an operational need and comply with applicable policy and practices.

Risk management - A documented process for the prospective (looking ahead) and recurring identification of what can go wrong, assigning a level of risk (e.g., High, Moderate, Low) to each risk, and planning and implementing mitigation steps for each commensurate with the level of risk.

Risk - A measure of the uncertainty of attaining a goal, objective, or requirement and the consequences of not attaining it. The uncertainty is the result of one or more undesirable Events that could occur during the system life cycle for which insufficient resources and time are programmed to overcome them. The consequences are inability to satisfy the operational military need and exceeding the programmed budget and directed schedule.

RRF - Ready Reserve Force

SA'AR - Corvette sized combatant built by Ingalls for Israeli Navy.

SC-21 - Next combatant ship program after DDG-51, also designated DD-21.

Scaleable - An attribute of design; develop designs, architectures, systems and transitions technologies that era adaptable across a range of end items (such as ship classes).

SCP – System Concept Paper, OBSOLETE, has been superceded by Integrated Program Summary (IPS)

Selected Acquisition Report (SAR) – report of program progress presented to congress for budgetary oversight.

SEMP – System Engineering Management Plan, includes plans for verification, risk alleviation, analyses and simulation of the system requirements.

Ship Production Model - A virtual representation of a particular ship being built at a shipyard

Shipbuild - New project planning and progress tracking software which will use some elements of System Dynamics

SFR - System Functional Review

SHP - Shaft Horse Power

Signature - Any attribute of any object by which a sensor can detect, locate and/or classify that object.

Significant accomplishment criteria - Specific, measurable conditions that must be satisfactorily demonstrated before a significant accomplishment listed in an Integrated Master Plan (IMP) is complete and before work dependent on the accomplishment can proceed.

Significant accomplishment - A specified step or result that indicates a level of progress toward completing an event and, in turn, meeting the objectives and requirements of the contract.

Simulation - The process of conducting experiments with a model (an abstraction or simplification) of an item and/or part or all of its operating environment for the purpose of assessing its behavior under selected conditions or of evaluating various strategies for its operation within the limits imposed by developmental or operational criteria. Simulation may include the use of analog or digital devices, laboratory models, or "test bed" sites. Simulations are usually programmed for solution on a computer; however, in the broadest sense, military exercises and war games are also simulations.

Specification tree - The hierarchical depiction of all the specifications needed to formally control the development, procurement, manufacture, integration, verification, and/or reprocurement during any part of the life cycle.

SSR - Systems Requirement Review, conducted to ascertain progress in defining system technical requirements. Determines the direction and progress of the systems engineering effort and the degree of convergence upon a balanced and complete configuration. Normally held during the CE/D phase, may be repeated after start of D/V to clarify the contractor's understanding of redefined/new user requirements.

STAR – System Threat Assessment Report, Documents the authoritative threat assessment tailored for and focused on a particular US defense acquisition program. Prepared by the Service intelligence agency and validated by DIA at milestones I, II, III & IV. Applicable to all threat driven defense acquisition programs. Must be system specific threat oriented.

Stealth - Ability to evade radar

Supportability - The degree to which planned logistics support (including system design; test, measurement, and diagnostic equipment; spares and repair parts; technical data; support and facilities; transportation requirements; training; manpower; and software support) allow meeting system availability and wartime usage requirements.

SUPSHIP - Supervisor of Shipbuilding

Survivability - The capability of a system to avoid or withstand man-made hostile environments without suffering an abortive impairment of its ability to accomplish its designated mission.

Sustainability - To prolong performance over a period of time.

System Dynamics - Methodology used to examine complex problems with non-linear relationships and feedback

System engineering - A process, applied iteratively throughout the System life cycle to translate stated objectives into design requirements, providing an integrated solution consisting of people, products and processes with the capability to satisfy the customer needs.

System - The entity to be designed as defined by the work breakdown structure. The entity for DD 21 Systems includes the ship and the infrastructure that supports ship operation, maintenance, readiness, etc.

Technical Performance Measure (TPM) - A parameter that is related to progress toward meeting the program or contract functional requirements or goals and is assessed periodically and at certain events to estimate the degree to which the final value will meet the anticipated or required level.

TEMP – Test and Evaluation Master Plan, an overall test and evaluation plan, designed to identify and integrate objectives, responsibilities, resources, and schedules for all test and evaluation to be accomplished prior to the subsequent key decision points. Prepared, as early as possible in the acquisition process, it is updated as development progresses.

Total Ownership Costs (TOC) – All the components of traditional Life Cycle Cost plus so-called linked, indirect costs (the fraction of supporting facilities/systems developed to support the given system.)

Traceability - The ability to relate an element of the functional baseline, functional architecture, physical hierarchy, allocated baseline, design baseline, and product baseline (or their representation in the decision data base) to any other element to which it has a master-subordinate (or parent-child) relationship.

Trade studies -: An objective comparison with respect to performance, cost, schedule, risk, and all other reasonable criteria of all realistic alternative requirements: architectures; baselines; or design, verification, manufacturing, deployment, training, operations, support, or disposal approaches.

Upgrade - A change from previously delivered items because of obsolescence of a part: a change in the military need or threat; an operational, supportability, or training deficiency is identified; the system life must be extended; a change in the law occurs; or an unsafe condition is detected.

Vensim - System Dynamics modeling software

WIP - Work In Progress

Work Breakdown Structure (WBS) - A product-oriented hierarchical tree composed of the hardware, software, services (including cross-product tasks such as systems engineering), data, and facilities that encompass all work to be carried out under the program or contract along with a dictionary of the entries in the tree. The WBS for the entire program is called the Program or Project WBS (PWBS). The WBS for the work under the contract is called the Contract WBS (CWBS) and is prepared in accordance with the contract.

Zones - Defines what functions are carried out in this portion of the ship e.g. Machinery, Living, Storage

8.4 Design Task, Discipline and Duration Resources

A vast quantity of material was analyzed to provide both general and specific data supporting the naval ship design process model. To specifically callout these references at each instance of assessment (Chapters 4 and 5) would be inappropriate. Therefore, the following list and brief descriptions of reference materials will be given to provide the reader with knowledge of those resources:

- Andy Summers, Contract Design History for the Guided Missile Destroyer (DDG 51 Class), Naval Sea Systems Command, Washington DC, June 1987. Contains contract design schedules, listings of resources (budgetary and personnel), listings of design products, descriptions of design processes and technical results.
- Andy Summers, DDG-51 Guided Missile Destroyer Preliminary Design History, Naval Sea Systems Command, Washington DC, June 1984. Contains preliminary design schedules, listings of resources (budgetary and personnel), listings of design products, descriptions of design processes and technical results.
- Barry Tibbitts, "Why Ships are Different", John J. McMullen Assoc., 1991. General description of design spiral elements and practical aspects of naval system engineering.
- Brown and Welsh, "FF13A Ship Design Math Model", Massachusetts Institute of Technology course Applications of Naval System Design, Fall 1996. A MathCAD model using parametrics to develop a balanced surface combatant design, model demonstrates physical and empirical relationships relative to the design process.
- C.R. Lloyd, Design Processes for the AEGIS Destroyer Program, Presentation by Bath Iron Works (BIW), November 18, 1997. Discussion of detailed design process, team structure and design products supporting the lead ship and manufacturing design of the DDG-51 class surface combatant.
- Doug Hilton, "PME IDEF Model", Naval Sea Systems Command, September 13, 1994. IDEF description of concept and preliminary design applicable to naval design using the Product Model Extension (PME) program.
- Edward Lewis, Principles of Naval Architecture, Society of Naval Architects and Marine Engineers, Jersey City, NJ, 1988. Detailed descriptions of all aspects of naval ship design including hydrostatics, hydrodynamics, structural analysis and design integration.
- Gale and Scott, "Early Stage Ship Design Seminar", Society of Naval Architects and Marine Engineers, October 1995. Discussion of the elements of the design spiral for concept design and the basic relationships among those elements.
- Greg Diggs, MAAST (Maritech Agile Shipbuilding Toolkit), Advanced Marine Enterprises Inc., March 26, 1997, http://www.advmar.com/framework/splash.htm. IDEF descriptions of complete design process for a generic "commercial" ship design.
- John Dalton, Implementation of Mandatory Procedures for Major and Non-Major Defense Acquisition Programs and Major and Non-Major Information Technology Acquisition Programs (SECNAVINST 5000.2B), Department of the Navy, Washington DC, December 6, 1996. Programmatic requirements relative to all phases of design process including listing of those design and risk assessment products required by law, statute and direction.

- John Dalton. Program Decision Process (SECNAVINST 5420.188E). Department of the Navy, Washington DC, October 31, 1995. Programmatic process description of those design products that must be presented at each milestone authorization.
- Karaszewski and Wade, Infrastructure Study in Shipbuilding: Report on Initial Findings Part 2, IDEFo Diagrams and Glossary, David Taylor Research Center, Bethesda, MA, January 3, 1991. IDEF descriptions of complete design process for a generic "commercial" ship design.
- Mahoney, Welsh and Moton. "13.412 DD13A Feasibility Design Requirements", Massachusetts Institute of Technology course Applications of Naval System Design, Fall 1997. Listing of design products required for concept and feasibility assessment of a surface combatant design.
- Myron Ricketts, Manual for Naval Surface Ship Design Technical Practices, Naval Sea Systems Command, Washington DC, 1980. Detailed descriptions of all design phases, all design products, and design inter-relationships necessary to enable individual NAVSEA engineers understand the impacts of design decisions on other design elements.
- Naval Surface Warfare Center Carderock Division, "Getting Started & Tutorials: Advanced Surface Ship Evaluation Tool (ASSET) Family of Ship Design Synthesis Programs", September 30, 1997. Description of the ASSET modules, formulations and synthesis structure.
- RADM Roger B. Horne, "Concept to Commissioning. Improving the Ship Design. Acquisition and Construction Process: Strategic Plan", Naval Sea Systems Command, Washington, DC, June 1991. Detailed analysis of naval ship design process including statistical assessment of design timelines and costs, interviews and suggestions from design participants, and design organization structures.
- Ron Nix, "T-AG9X Preliminary/Contract Design Estimates", Naval Sea Systems Command, January 16, 1987. Listing of design products, timelines and iterations (presented by design discipline and sub-discipline) estimated for an auxiliary ship.
- Scott Ripley, "Pre-Contract Product Development-Process Flow Chart", Newport News Shipbuilding, December 11, 1996. IDEF diagram for all processes (engineering, cost, programmatic, legal, etc.) related to the development of an aircraft carrier.
- Ship Design Group, Ship Design Project Histories: Volume I, II and III, Naval Sea Systems Command, September 1978, May 1986 and August 1996. Complete descriptions of concept through contract design for all naval ship designs developed from 1970 through 1996. Includes manpower allocation, design disciplines, costs, ship descriptions and timelines.
- Storch, Hammon, Bunch and Moore, Ship Production, Society of Naval Architects and Marine Engineers, Jersey City, NJ, 1995. Generic description of design products, design organization and production considerations relative to general ship design.

8.5 Baseline DDG-51 Task and Productivity Levels

The following data has been extrapolated from the references in Chapter 8.4 and was used to calibrate the Naval Ship Design Process Model.

Node	Task Element	Average ManMonths Per Task (Adjusted for DDG-51 Program)					
		Concept	Preliminary	Contract	Detailed		All
					Plans	Construct	
Programmatic	Program Management Tasks	0.63	1.18	11.37	9.65	11.41	6.85
	Requirements & Assessment	0.21	0.38	5.86	4.96	5.84	3.45
	Risk Mitigation & Coordination	0.07	0.38	3.96	3.22	3.90	2.30
Systems Engineering	Logistics and Reliability Engineering	1.02	8.24	11.72	16.81	20.35	11.63
	Design Integration & Specifications	6.61	7.36	15.94	15.87	17.93	12.74
	Producibility and Production Engineering	2.55	21.28	11.75	17.63	21.35	14.91
	Performance-Requirements Assessment	3.36	5.57	6.20	7.12	8.62	6.18
	Manning	1.69	2.01	2.06	3.93	4.76	2.89
Hull Engineering	Hull Geometry	1.97	5.57	1.97	3.16	3.82	3.30
	Weight, Hull Subdivision & Hydrostatic Design	1.96	5.57	0.19	0.63	0.76	1.82
	Hydrodynamics-Resistance	2.55	5.57	8.82	11.35	13.51	8.36
	Hydrodynamics-Seakeeping	2.55	5.57	8.82	11.35	13.51	8.36
	Hydrodynamics-Maneuvering, Appendage & Propeller Design	2.55	5.57	1.26	1.01	1.22	2.32
	Structures-Static and Dynamic Design	0.61	5.57	1.25	1.19	1.44	2.01
	Space and Arrangements	1.27	0.15	2.29	2.02	2.20	1.59
Machinery Systems Engineering	Machinery Systems Design and Integration	3.57	5.86	1.75	5.03	5.93	4.43
	Propulsion Systems	0.77	0.62	1.38	1.69	2.05	1.30
	Electrical Systems	0.77	0.62	1.38	1.69	2.05	1.30
	Auxiliary and Support Systems	1.30	0.84	5.42	5.06	6.13	3.75
	Deck, Handling and Aircraft Support Systems	1.28	1.47	0.30	1.57	1.90	1.30
Mission Systems Engineering	Mission Systems Selection, Design and Integration	3.56	1.94	1.81	3.70	4.48	3.10
	Topside Design and Integration	13.02	1.24	2.60	6.26	7.58	6.14
Cost	Cost Estimates & Analysis	0.61	1.02	5.29	4.23	5.13	3.26
Totals and Averages		2.37	4.07	4.93	6.05	7.21	4.93

Node	Task Element	Analysis and Approval Periods (workdays)				
		Average for 45 Programs from CNA Study			CG-47	DDG-51
		NAVSEA	PMO	Review/Approval Chain	Review/Approval Chain	
Programatic	Program Management Tasks	3.6	42.5	46.3		
	Requirements & Assessment	6.4	53.0	76.3	100.0	24.0
	Risk Mitigation & Coordination	7.5	115.0	140.0		
Systems Engineering	Logistics and Reliability Engineering					
	Design Integration & Specifications					
	Producibility and Production Engineering	0.5	15.0	50.0		
	Performance-Requirements Assessment					
	Manning					
Hull Engineering	Hull Geometry					
	Weight, Hull Subdivision & Hydrostatic Design					
	Hydrodynamics-Resistance					
	Hydrodynamics-Seakeeping					
	Hydrodynamics-Maneuvering, Appendage & Propeller Design					
	Structures-Static and Dynamic Design					
	Space and Arrangements					
Machinery Systems Engineering	Machinery Systems Design and Integration					
	Propulsion Systems					
	Electrical Systems					
	Auxiliary and Support Systems					
	Deck, Handling and Aircraft Support Systems					
Mission Systems Engineering	Mission Systems Selection, Design and Integration					
	Topside Design and Integration					
Cost	Cost Estimates & Analysis	9.4	10.0	35.0		
Totals and Averages		5.2	31.7	57.5	33.3	8.0

Node	Task Element	Node - Task		Concept	Preliminary	Contract	Average Number of Design Tasks: Detailed: Functional	Transition	Zonal	Production	Total
Programatic	Program Management Tasks	A	1	8	10	13	13	14	14	14	55
	Requirements & Assessment	A	2	8	8	8	8	8	9	9	34
	Risk Mitigation & Coordination	A	3	12	13	13	13	13	13	13	52
Systems Engineering	Logistics and Reliability Engineering	B	1	2	2	2	2	2	2	2	8
	Design Integration & Specifications	B	2	1	3	4	4	5	5	5	19
	Producibility and Production Engineering	B	3	1	2	2	3	3	3	3	12
	Performance-Requirements Assessment	B	4	4	5	5	5	5	5	5	20
	Manning	B	5	2	4	4	4	4	4	4	16
Hull Engineering	Hull Geometry	C	1	4	4	4	4	4	4	4	16
	Weight, Hull Subdivision & Hydrostatic Design	C	2	6	19	20	20	20	20	20	80
	Hydrodynamics-Resistance	C	3	2	2	2	2	2	2	2	8
	Hydrodynamics-Seakeeping	C	4	1	1	2	2	2	2	2	8
	Hydrodynamics-Maneuvering, Appendage & Propeller Design	C	5	2	11	11	11	11	11	11	44
	Structures-Static and Dynamic Design	C	6	7	15	18	18	18	18	18	72
	Space and Arrangements	C	7	5	16	16	17	17	20	20	74
Machinery Systems Engineering	Machinery Systems Design and Integration	D	1	3	8	9	11	12	12	12	47
	Propulsion Systems	D	2	2	7	8	8	8	8	8	32
	Electrical Systems	D	3	2	7	8	8	8	8	8	32
	Auxiliary and Support Systems	D	4	2	12	14	14	14	14	14	56
	Deck, Handling and Aircraft Support Systems	D	5	1	7	7	7	7	7	7	28
Mission Systems Engineering	Mission Systems Selection, Design and Integration	E	1	3	9	10	10	10	10	10	40
	Topside Design and Integration	E	2	2	5	5	5	5	5	5	20
Cost	Cost Estimates & Analysis	F	1	3	4	6	6	6	6	6	24
Total and Averages				83	174	191	195	198	202	202	797

8.6 Programmatic Task Development and Processing

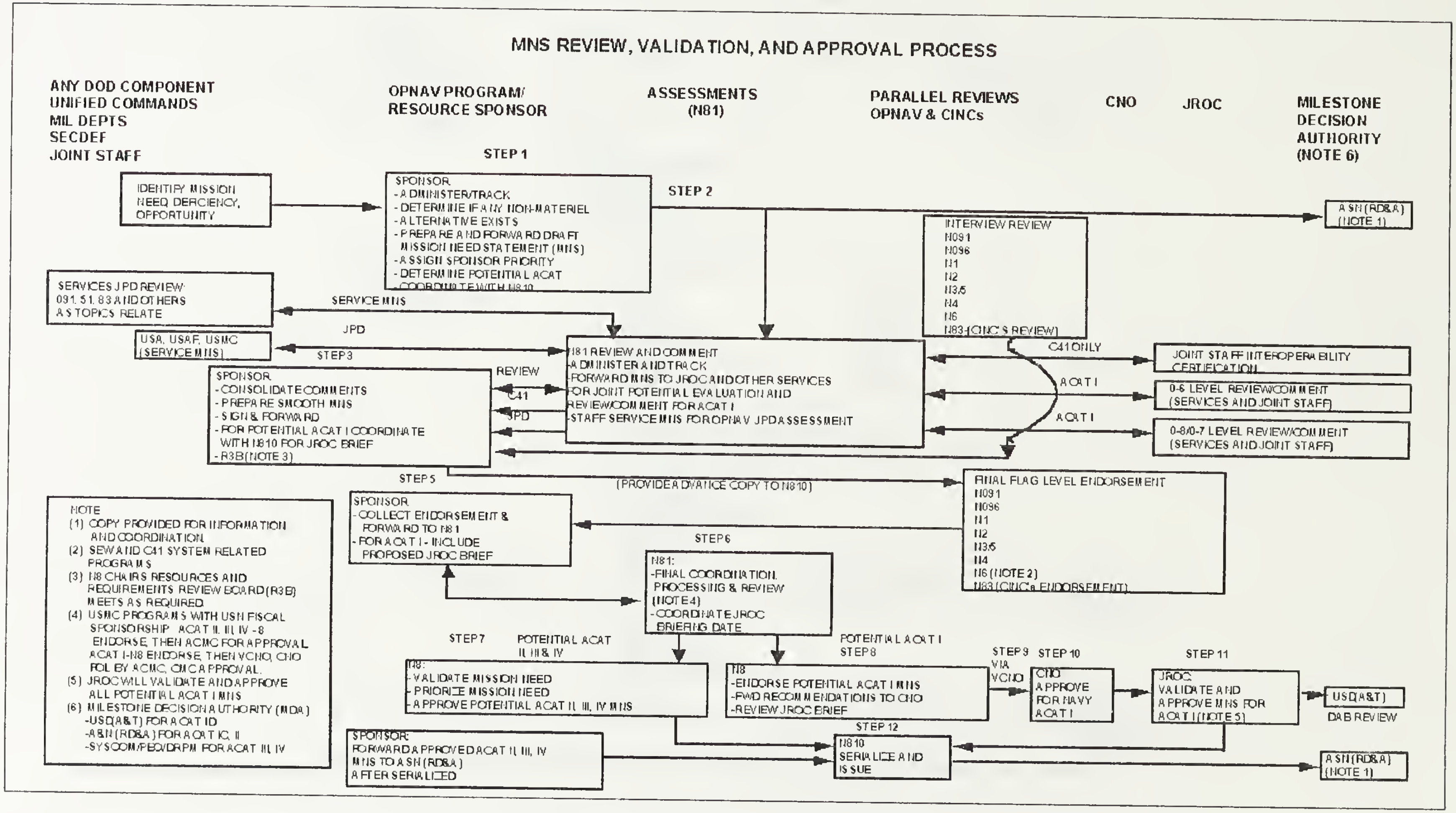

Figure 61 Mission Need Statement (MNS) Review, Validation and Approval Process[162]

[162] John Dalton, Implementation of Mandatory Procedures for Major and Non-Major Defense Acquisition Programs and Major and Non-Major Information Technology Acquisition Programs (SECNAVINST 5000.2B), Department of the Navy, Washington DC, December 6, 1996, Appendix II.

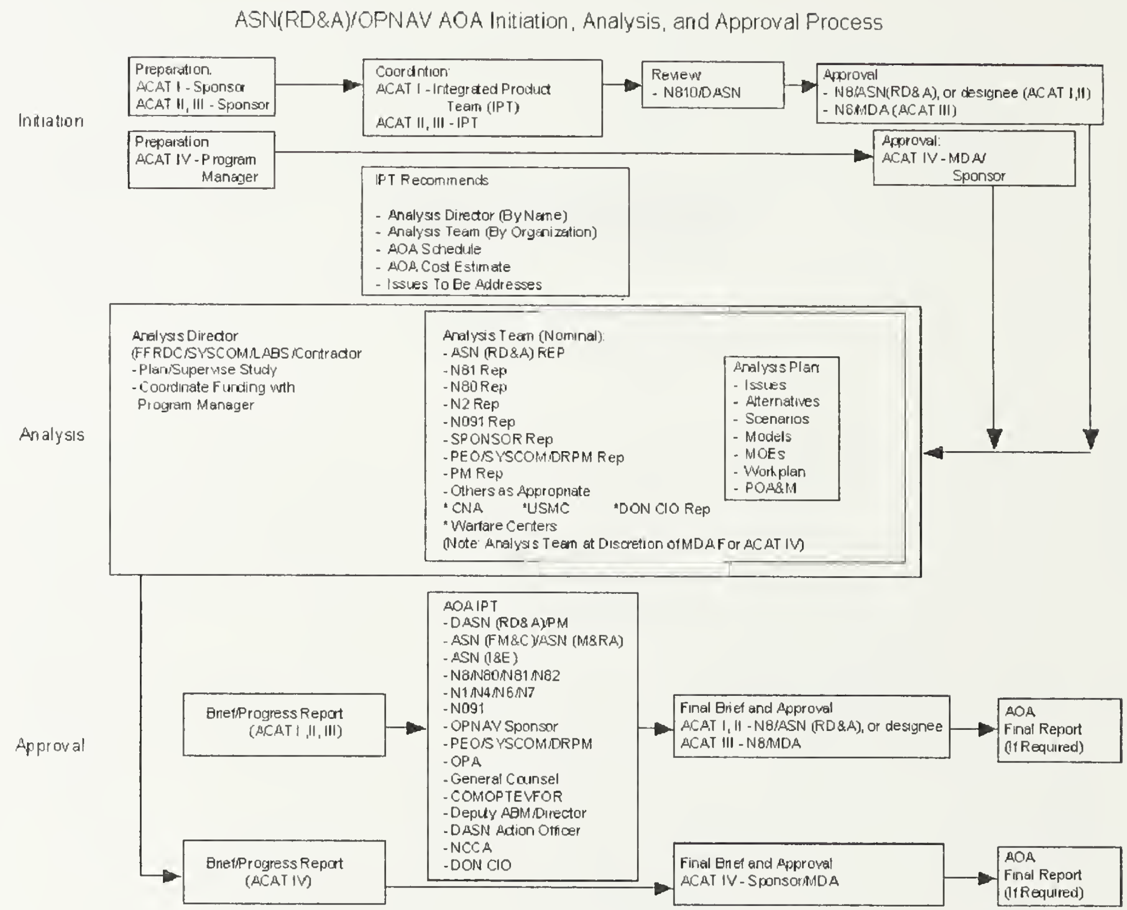

Figure 62 Analysis of Alternatives (AoA) Initiation, Analysis and Approval Process[163]

[163] Ibid.

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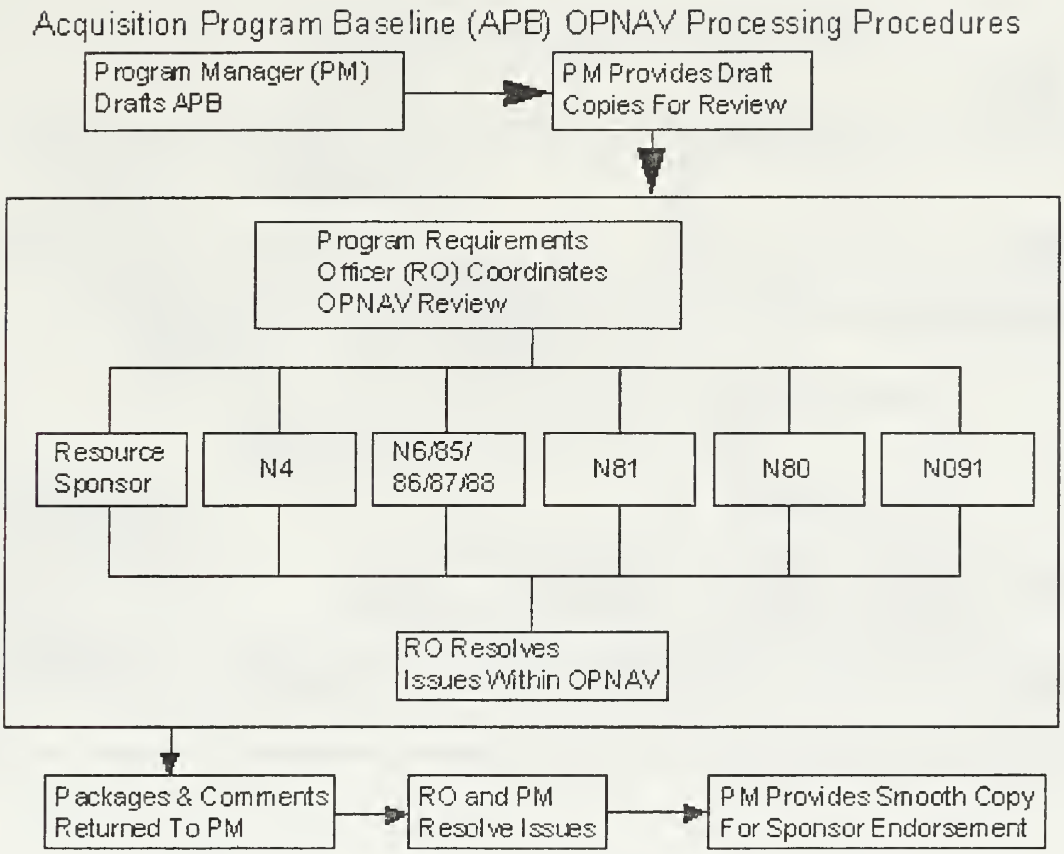

Figure 63 Acquisition Program Baseline (APB) Processing Procedures[164]

[164] Ibid.

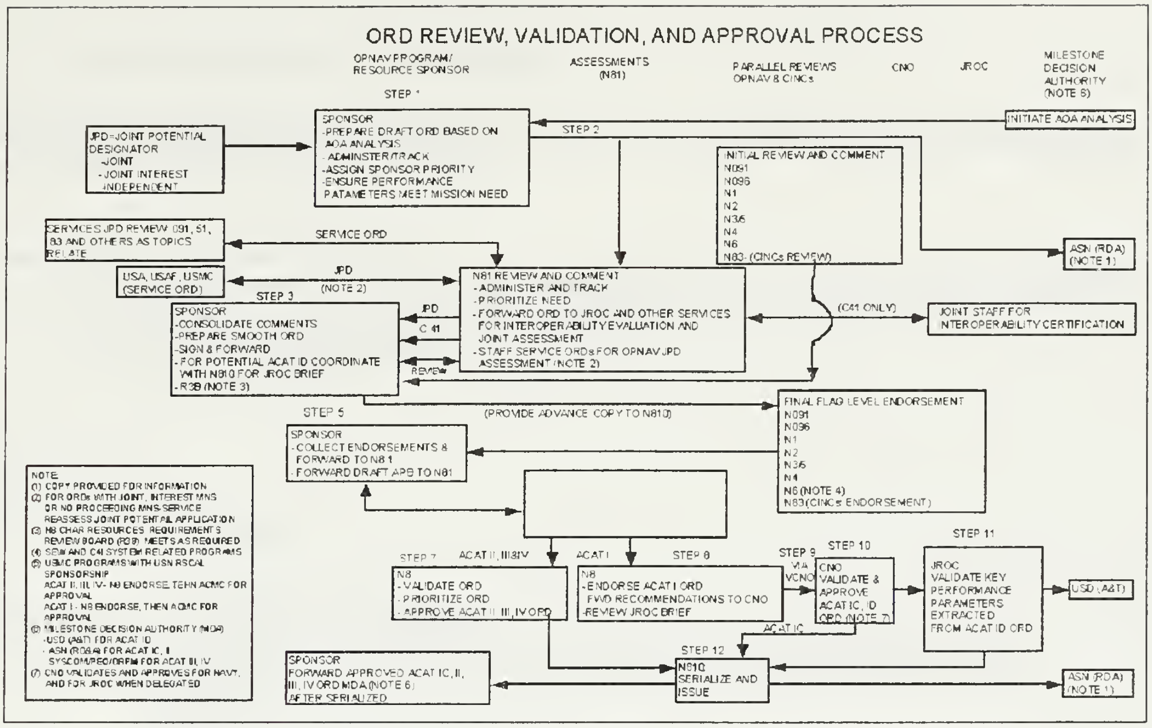

Figure 64 Operational Requirements Document (ORD) Review, Validation and Approval Process[165]

[165] Ibid.

8.7 Naval Ship Design Process Model

The following formulations are shown in the format of Vensim code. For electronic copies of the formulation, contact the author at tomkimlav@sprintmail.com.

```
Contracted Assign Rate[Phase,Discipline]=
	Current Phase[Phase]*MIN(Contractor New Assignments[Phase,Discipline]/Contractor Assign Period\
		[Phase],Contractors Available[Phase,Discipline
	]/Contractor Assign Period[Phase])
	~	Manpower/Month
	~		|

Adjust Rate[Phase]=
	0.4,0.3,0.3,1.1,0.7
	~	Dimensionless
	~		|

Adjusted Desired Manpower[Phase,Discipline]=
	Desired Manpower[Phase,Discipline]*Effect of Schedule Gap on Desired Manpower[Phase,\
		Discipline]
	~	Manpower
	~		|

Effect of Schedule Gap on Overtime[Phase,Discipline]=
	Effect of Schedule Gap on Overtime f(Schedule Gap[Phase,Discipline])
	~	Dimensionless
	~		|

Net Contractors=
	SUM(Contractors Phase[Phase!])
	~	Manpower
	~		|

Effective Experienced[Phase,Discipline]=
	Contractor Experienced[Phase,Discipline]*Overtime[Phase,Discipline]
	~	Manpower
	~	Experienced Contractor times assigned overtime
	|

Maximum Overtime=
	1.75
	~	Dimensionless
	~	Maximum monthly overtime that may be assigned of personnel
	|

Phase Task Change[Phase,Discipline]=
	Rescope Rate[Phase,Discipline]
	~	Tasks/Month
	~		|

Effect of Approval Phase on Desired Manpower[Phase]=
	Effect of Approval Phase on Desired Manpower f(Approval Phase[Phase])
```

```
	~	Dimensionless
	~		|

Phase Tasks[Phase,Discipline]= INTEG (
	Phase Task Change[Phase,Discipline],
		Initial Tasks[Phase,Discipline])
	~	Tasks
	~		|

NAVSEA Assign Rate[Phase,Discipline]=
	Current Phase[Phase]*MIN(NAVSEA New Assignments[Phase,Discipline]/NAVSEA Assign Period\
		,NAVSEA Available[Phase,Discipline]/NAVSEA Assign Period
	)
	~	Manpower/Month
	~		|

Rescope Rate[Phase,Discipline]=
	Current Phase[Phase]*Rescope Fraction[Phase]*MAX(0,Input)*Initial Tasks[Phase,Discipline\
		]/Approval Period[Phase]
	~	Tasks/Month
	~	The rate of design rescope by the DoN/DoD is indicator that the phase \
		impacted by rescope is the current phase (equals 1) times a random \
		generation of desired change introduction (input) times the a fraction of \
		the baseline (initial) tasks involved in the rescope over the time \
		required to introduce rescope (a period concurrent with the approval \
		period)
	|

Net Productivity Rate[Phase,Discipline]=
	Adjust Rate[Phase]*Avg Design Rate[Phase,Discipline]*EffectOfFatigueOnProductivity[Phase\
		,Discipline]*EffectOfScheduleGapOnProductivity
	[Phase,Discipline]*Effect of Personnel Level on Productivity[Phase,Discipline]
	~	Tasks/(Manpower*Month)
	~		|

Contractor New Released[Phase,Discipline]=
	IF THEN ELSE(Current Phase[Phase]=0,Contractor New[Phase,Discipline]/Contractor Release Period\
		,MIN(Contractor New Desired Release[Phase,Discipline]/Contractor Release Period,Contractor
New\
		[Phase,Discipline]/Contractor Release Period))
	~	Manpower/Month
	~		|

Effect of NAVSEA Percent[Phase,Discipline]=
	Effect of NAVSEA Percent f(NAVSEA Percentage[Phase]/NAVSEA Participation Desired Percentage\
		[Phase,Discipline])
	~	Dimensionless
	~		|

NAVSEA New Release Rate[Phase,Discipline]=
	IF THEN ELSE(Current Phase[Phase]=0,NAVSEA New[Phase,Discipline]/NAVSEA Release Period\
		,MIN(NAVSEA New Desired Release[Phase,Discipline]/NAVSEA Release Period,NAVSEA
New[\
		Phase,Discipline]/NAVSEA Release Period))
	~	Manpower/Month
```

~ Release of new project personnel is the minimum of the desired release and \
the release constraint (manning over time required to release personnel)
|

Desired Duration[Phase]=
18,8,10,16,6
~ Month
~ |

Avg Design Rate[Concept,Discipline]=
1.58, 4.8, 15.36, 0.98, 0.15, 0.39, 0.3, 0.59, 0.51, 0.51, 0.39, 0.39, 0.39, 1.64, 0.79\
, 0.28, 1.3, 1.3, 0.77, 0.78, 0.28
, 0.08, 1.64 ~~|
Avg Design Rate[Preliminary,Discipline]=
0.85, 2.63, 2.63, 0.12, 0.14, 0.05, 0.18, 0.5, 0.18, 0.18, 0.18, 0.18, 0.18, 0.18, 6.83\
, 0.17, 1.62, 1.62, 1.19, 0.68,
0.52, 0.8, 0.98 ~~|
Avg Design Rate[Contract,Discipline]=
0.09, 0.17, 0.25, 0.09, 0.06, 0.09, 0.16, 0.49, 0.51, 5.15, 0.11, 0.11, 0.8, 0.8, 0.44\
, 0.57, 0.72, 0.72, 0.18, 3.35, 0.55
, 0.38, 0.19 ~~|
Avg Design Rate[Lead Ship,Discipline]=
0.1, 0.2, 0.31, 0.06, 0.06, 0.06, 0.14, 0.25, 0.32, 1.6, 0.09, 0.09, 0.99, 0.84, 0.5\
, 0.2, 0.59, 0.59, 0.2, 0.64, 0.27,
0.16, 0.24 ~~|
Avg Design Rate[Manufacturing,Discipline]=
0.09, 0.17, 0.26, 0.05, 0.06, 0.05, 0.12, 0.21, 0.26, 1.32, 0.07, 0.07, 0.82, 0.69, \
0.45, 0.17, 0.49, 0.49, 0.16, 0.53,
0.22, 0.13, 0.2
~ Tasks/(Month*Manpower)
~ |

Baseline Desired Manning[Phase,Discipline]=
Initial Tasks[Phase,Discipline]/(Avg Design Rate[Phase,Discipline]*Desired Duration[\
Phase])
~ Manpower
~ Baseline Manning Requirement is the Number of Tasks over the tasks per man \
required to meet the desired schedule
|

Effect of Schedule Gap on Overtime f(
[(0,0)-(10,2)],(0,1),(1,1),(2,1),(10,2))
~ Dimensionless
~ For schedule gap of 1 or less\!\!\!
|

Initial Schedule Projection[Concept]=
Desired Duration[Concept] ~~|
Initial Schedule Projection[Preliminary]=
Desired Duration[Concept]+Desired Duration[Preliminary] ~~|
Initial Schedule Projection[Contract]=
Desired Duration[Concept]+Desired Duration[Preliminary]+Desired Duration[Contract] ~~|
Initial Schedule Projection[Lead Ship]=
Desired Duration[Concept]+Desired Duration[Preliminary]+Desired Duration[Contract]+Desired Duration\
[Lead Ship] ~~|

Initial Schedule Projection[Manufacturing]=
Desired Duration[Concept]+Desired Duration[Preliminary]+Desired Duration[Contract]+Desired Duration\
[Lead Ship]+Desired Duration[Manufacturing]
~ Month
~ |

Net Desired Manpower=
SUM(Desired Manpower Phase[Phase!])
~ Manpower
~ |

NAVSEA Participation Adjusted Percentage[Phase,Discipline]=
NAVSEA Participation Desired Percentage[Phase,Discipline]*Effect of NAVSEA Percent[Phase\
,Discipline]
~ Dimensionless
~ The desired manning level of NAVSEA relative to Contractors
|

NAVSEA Participation Desired Percentage[Phase,Discipline]=
MIN(NAVSEA Participation Nominal Percentage[Phase],NAVSEA Participation Nominal Percentage\
[Phase]*Effect of Approval Phase on NAVSEA Percent
[Phase]*Effect of Available Budget on NAVSEA Percent[Phase])
~ Dimensionless
~ |

Total Contractors Assigned[Phase]=
(SUM(Effective Experienced[Phase,Discipline!])+SUM(Effective New[Phase,Discipline!])\
)*Current Contract Fee[Phase]
~ Manpower
~ The total contractors assigned as a cost is the sum of current contractors \
times the additional percentage charged to current contracts (10% overhead \
fee)
|

NAVSEA Percentage[Phase]=
NAVSEA Phase[Phase]/MAX(1,NAVSEA Phase[Phase]+Contractors Phase[Phase])
~ Dimensionless
~ |

NAVSEA Experienced Release Rate[Phase,Discipline]=
IF THEN ELSE(Current Phase[Phase]=0,NAVSEA Experienced[Phase,Discipline]/NAVSEA Release Period\
,MIN(NAVSEA Exp Desired Release[Phase,Discipline]/NAVSEA Release Period,NAVSEA Experienced\
[Phase,Discipline
]/NAVSEA Release Period))
~ Manpower/Month
~ Release of experienced personnel is the minimum of the desired release and \
the release constraint (manning over time required to release personnel)
|

Desired Manpower[Phase,Discipline]=
MAX(DesiredAccomplishingRate[Phase,Discipline] / (Avg Design Rate[Phase,Discipline]\
*Adjust Rate[Phase]),Baseline Desired Manning[Phase,Discipline])
~ Manpower

~ |

Net NAVSEA=
SUM(NAVSEA Phase[Phase!])
~ Manpower
~ |

Contractor Experience Release Rate[Phase,Discipline]=
IF THEN ELSE(Current Phase[Phase]=0,Contractor Experienced[Phase,Discipline]/Contractor Release Period\
,MIN(Contractor Exp Desired Release[Phase,Discipline]/Contractor Release Period,Contractor Experienced\
[Phase,Discipline]
/Contractor Release Period))
~ Manpower/Month
~ |

Schedule Shift[Concept,Discipline]=
(Indicated Completion Date[Concept,Discipline]-Desired Schedule[Concept,Discipline])\
/Time to Shift Schedule ~~|
Schedule Shift[Preliminary,Discipline]=
MAX(Indicated Completion Date[Concept,Discipline]-Desired Schedule[Concept,Discipline\
],Indicated Completion Date[Preliminary,Discipline]-Desired Schedule[Preliminary,Discipline\
])/Time to Shift Schedule ~~|
Schedule Shift[Contract,Discipline]=
MAX(Indicated Completion Date[Concept,Discipline]-Desired Schedule[Concept,Discipline\
],MAX(Indicated Completion Date[Preliminary,Discipline]-Desired Schedule[Preliminary\
,Discipline],Indicated Completion Date
[Contract,Discipline]-Desired Schedule[Contract,Discipline]))/Time to Shift Schedule\
~~|
Schedule Shift[Lead Ship,Discipline]=
MAX(Indicated Completion Date[Concept,Discipline]-Desired Schedule[Concept,Discipline\
],MAX(Indicated Completion Date[Preliminary,Discipline]-Desired Schedule[Preliminary\
,Discipline],MAX(Indicated Completion Date
[Contract,Discipline]-Desired Schedule[Contract,Discipline],Indicated Completion Date\
[Lead Ship,Discipline]-Desired Schedule[Lead Ship,Discipline])))/Time to Shift Schedule\
~~|
Schedule Shift[Manufacturing,Discipline]=
MAX(Indicated Completion Date[Concept,Discipline]-Desired Schedule[Concept,Discipline\
],MAX(Indicated Completion Date[Preliminary,Discipline]-Desired Schedule[Preliminary\
,Discipline],MAX(Indicated Completion Date
[Contract,Discipline]-Desired Schedule[Contract,Discipline],MAX(Indicated Completion Date\
[Lead Ship,Discipline]-Desired Schedule[Lead Ship,Discipline],Indicated Completion Date\
[Manufacturing,Discipline
]-Desired Schedule[Manufacturing,Discipline]))))/Time to Shift Schedule
~ Month/Month
~ The shift of design schedule is the indicated completion date over the \
time required to initiate the full time shift...note that each phase date \
is shift by preceding phase schedule shifts as well
|

Percent Phase Complete[Phase]=
Total Approved Tasks[Phase]/SUM(Phase Tasks[Phase,Discipline!])
~ Dimensionless
~ The Percent Completion of the current phase is the ratio of the total \

approved tasks to the total phases tasks initially required to be done
|

Current Contract Fee[Phase]=
Percentage of RFP Contracts[Phase]*1+(1-Percentage of RFP Contracts[Phase])*1.1
~ Dimensionless
~ The current contract fee represents the effective cost of contractors as a \
function of those contracted at RFP rate (100% cost) and those on current \
NAVSEA contracts (additional 10% overhead to cost)
|

Overtime[Phase,Discipline]=
MIN(Maximum Overtime,Effect of Schedule Gap on Overtime[Phase,Discipline]*Overtime f\
(Indicated Overtime Required[Phase,Discipline]))
~ fraction
~ The current assigned overtime is the maximum of maximum overtime to assign \
and the overtime profile (assignment schedule) for a given indicated \
overtime requirement
|

Effect of NAVSEA Percent f(
[(0,0)-(1,1)],(0,1),(0.5,1),(0.75,0.75),(1,0))
~ Dimensionless
~ |

Effective New[Phase,Discipline]=
Contractor New[Phase,Discipline]*Overtime[Phase,Discipline]
~ Manpower
~ New Contractors times the overtime assigned
|

Prob Discovery by Phase[Phase]=
0.4,0.37,0.3,0.23,0.2
~ Dimensionless
~ The probability of discovery of an error increases for each phase as more \
individuals are involved with the project and increasing detail is examined
|

Prob Defect Discovery[Phase,Discipline]=
Effect of Errors on Discovery[Phase,Discipline]*Prob Discovery by Phase[Phase]
~ Tasks/Tasks
~ Probability of Discovery by Design Phase times the changing probability of \
discovery (Effect of Errors on Discovery) as the total errors for the \
current phase increases
|

Comp Rate f[Phase,Discipline]=
MIN(WIP[Phase,Discipline]/Min Comp Period[Phase,Discipline],Effective Personnel Level\
[Phase,Discipline]*Net Productivity Rate
[Phase,Discipline])
~ Tasks/Month
~ The average completion rate for the WIP remaining in each discipline \
during each phase is the lesser of time limited completion (WIP/minimum \
period to complete) and resource limited completion (personnel available \
times net rate of productivity per person)

|

Review Rate[Phase,Discipline]=
Review Phase[Phase]*Completed[Phase,Discipline]/Review Period[Phase]
~ Tasks/Month
~ The rate of NAVSEA Review of Tasks is the completed tasks over the time \
required to review a task...note that this assumes task review is \
continuous (more likely this is not the case...and leads to the \
possibility of draining completed tasks prior to proper iteration through \
the feedback matrix...
|

Review Ratio Actual[Phase]=
(SUM(Completed[Phase,Discipline!])+SUM(Approved[Phase,Discipline!])+SUM(Review[Phase\
,Discipline!]))/SUM(Initial Tasks[Phase,Discipline!])
~ Dimensionless
~ The Ratio of total tasks available for or already approved to the total \
intial tasks is the total of tasks released at review and those residing \
as Approved divided by the initial tasks...by phase.
|

Review Ratio Desired[Phase]=
0.8, 0.9, 0.95, 0.5, 0.5
~ Tasks/Tasks
~ |

Review Error Rate f[Phase,Discipline]=
Adj Prob Defect[Phase,Discipline]*Prob Defect Discovery[Phase,Discipline]*(Review[Phase\
,Discipline]/Time to Detect Errors[Phase])
~ Tasks/Month
~ |

Review Phase[Phase]=
Review Phase Effect f(Review Ratio Actual[Phase]/Review Ratio Desired[Phase])
~ Dimensionless
~ The approval phase is active (1) for actual to desired ratios greater than \
1 and inactive (0) for ratios less than 1
|

Review Phase Effect f(
[(0,0)-(2,1)],(0,0),(0.537764,0.0921053),(0.773414,0.25),(0.954683,0.820175),(1,1),(\
2,1))
~ Dimensionless
~ The approval Phase Effect Function compares the ratio of Approval Ratio \
Actual to Desired, for net ratios greater than 1, the approval phase is \
active (1) for ratio less than 1 the approval phase is not active (0)\!\!
|

Review Phase Net=
SUM(Review Phase[Phase!])
~ Dimensionless
~ |

Internal Error Rate f[Phase,Discipline]=
Adj Prob Defect[Phase,Discipline]*Prob Defect Discovery[Phase,Discipline]*(Completed\

[Phase,Discipline]/Time to Detect Errors[Phase])
~ Tasks/Month
~ |

EffectOfScheduleGapOnProductivity[Phase,Discipline]=
EffectOfScheduleGapOnProductivity f(Schedule Gap[Phase,Discipline\
])
~ dmnl
~ |

Adj Prob Defect[Phase,Discipline]=
Prob Defect by Phase[Phase]*Effect of Errors on Defects[Phase,Discipline]
~ Tasks/Tasks
~ |

NAVSEA Experienced[Phase,Discipline]= INTEG (
NAVSEA Experience Gain Rate[Phase,Discipline]-NAVSEA Experienced Release Rate[Phase,\
Discipline],
0)
~ Manpower
~ The accumulation of NAVSEA personnel with direct experience with the \
current design Project is 0 plus the rate of experience gain less the \
release rate of experienced personnel from the project
|

NAVSEA Available[Phase,Discipline]= INTEG (
NAVSEA New Release Rate[Phase,Discipline]+NAVSEA Experienced Release Rate[Phase,Discipline\
]-NAVSEA Assign Rate[Phase,Discipline],
NAVSEA Baseline Personnel[Phase,Discipline])
~ Manpower
~ |

Effect of Errors on Defects[Phase,Discipline]=
Effect of Errors on Defects f(Errors Discovered[Phase,Discipline]/Initial Tasks[Phase\
,Discipline])
~ Dimensionless
~ |

Effect of Errors on Defects f(
[(0,0)-(1,1)],(0,1),(0.001,0.9),(0.01,0.8),(0.1,0.5),(0.247734,0.0745614),(1,0))
~ Dimensionless
~ |

Effect of Errors on Discovery[Phase,Discipline]=
Effect of Errors on Discovery f(Errors Discovered[Phase,Discipline]/Initial Tasks[Phase\
,Discipline])
~ Dimensionless
~ |

NAVSEA Experience Gain Rate[Phase,Discipline]=
NAVSEA New[Phase,Discipline]/NAVSEA Experience Gain Period[Phase]
~ Manpower/Month
~ The rate of transfer of personnel from new to project to experienced with \
the project is the number of personnel over the average time to acquire \
experience

```
	|

Error Discovery Rate[Phase,Discipline]=
	Internal Error Rate[Phase,Discipline]+Review Error Rate[Phase,Discipline]
	~	Tasks/Month
	~		|

NAVSEA New[Phase,Discipline]= INTEG (
	NAVSEA Assign Rate[Phase,Discipline]-NAVSEA Experience Gain Rate[Phase,Discipline]-NAVSEA
New Release Rate\
		[Phase,Discipline]
	,
		0)
	~	Manpower
	~		|

Prob Defect by Phase[Phase]=
	0.2,0.19,0.15,0.11,0.1
	~	Dimensionless
	~	Probability of a defect will change with each phase due to increasing \
		individuals and detail
	|

Total Errors per Phase[Phase]=
	SUM(Errors Discovered[Phase,Discipline!])
	~	Tasks
	~		|

Effect of Errors on Discovery f(
	[(0,0)-(1,1)],(0,1),(0.001,0.9),(0.01,0.8),(0.1,0.5),(0.5,0.1),(1,0))
	~	Dimensionless
	~		|

Errors Discovered[Phase,Discipline]= INTEG (
	Error Discovery Rate[Phase,Discipline],
		0)
	~	Tasks
	~		|

Indicated Overtime Required[Phase,Discipline]=
	IF THEN ELSE(Personnel Assigned[Phase,Discipline]<=0,Adjusted Desired Manpower[Phase\
		,Discipline]/Man,Adjusted Desired Manpower
	[Phase,Discipline]/Personnel Assigned[Phase,Discipline])
	~	Dimensionless
	~		|

Man=
	1
	~	Manpower
	~	The unit for a single person
	|

Effect of Personnel Level on Productivity[Phase,Discipline]=
	Effect of Personnel Level on Productivity f(Personnel Assigned[Phase,Discipline]/Man\
		)
```

~ Dimensionless
~ Described in literature as "communication overhead", increased levels of \
personnel assigned to a project can adversely effect productivity from the \
standpoint of required personnel interaction, and down time for meetings, \
etc...
|

Design Spiral Rate[Phase,Discipline]=
Feedback Fraction[Phase]*MIN(Completed[Phase,Discipline]/TIME STEP,MAX(Comp Rate[Phase\
,A1]*Design Spiral Matrix
[A1,Discipline
],MAX(Comp Rate[Phase,A2]*Design Spiral Matrix[A2,Discipline],MAX(Comp Rate[Phase,A3\
]*Design Spiral Matrix[A3,Discipline],MAX(Comp Rate
[Phase,B1]*Design Spiral Matrix[B1,Discipline],MAX(Comp Rate[Phase,B2]*Design Spiral Matrix\
[B2,Discipline],MAX(Comp Rate[Phase,B3
]
*Design Spiral Matrix[B3,Discipline],MAX(Comp Rate[Phase,B4]*Design Spiral Matrix[B4\
,Discipline],MAX(Comp Rate[Phase,B5]*Design Spiral Matrix
[B5,Discipline],MAX(Comp Rate[Phase,C1]*Design Spiral Matrix[C1,Discipline],MAX(Comp Rate\
[Phase,C2]*Design Spiral Matrix[C2,Discipline
],MAX(Comp Rate[Phase,C3]*Design Spiral Matrix[C3,Discipline],MAX(Comp Rate[Phase,C4\
]*Design Spiral Matrix[C4,Discipline],MAX(Comp Rate
[Phase,C5]*Design Spiral Matrix[C5,Discipline],MAX(Comp Rate[Phase,C6]*Design Spiral Matrix\
[C6,Discipline],MAX(Comp Rate[Phase,C7
]
*Design Spiral Matrix[C7,Discipline],MAX(Comp Rate[Phase,D1]*Design Spiral Matrix[D1\
,Discipline],MAX(Comp Rate[Phase,D2]*Design Spiral Matrix
[D2,Discipline],MAX(Comp Rate[Phase,D3]*Design Spiral Matrix[D3,Discipline],MAX(Comp Rate\
[Phase,D4]*Design Spiral Matrix[D4,Discipline
],MAX(Comp Rate[Phase,D5]*Design Spiral Matrix[D5,Discipline],MAX(Comp Rate[Phase,E1\
]*Design Spiral Matrix[E1,Discipline],MAX(Comp Rate
[Phase,E2]*Design Spiral Matrix[E2,Discipline],Comp Rate[Phase,F1]*Design Spiral Matrix\
[F1,Discipline]))))))))))))))))))))))
~ Tasks/Month
~ Design feedback (due to concurrent design assumptions inherent to the \
Naval Design Process) is the fraction of impacted design tasks (Feedback \
fraction) times the minimum of completed tasks rate constraint (completed \
over design phase time measure...one month) and the maximum "work \
interference" rate for the given discipline compared to the other 22 \
disciplines (Feedback matrix times the disciplines completion rate)
|

Effect of Personnel Level on Productivity f(
[(0,0)-(100,1)],(0,1),(25.6798,0.964912),(52.8701,0.894737),(80.0604,0.714912),(100,\
0.5))
~ Dimensionless
~ |

Funding Period=
12
~ Month
~ |

Rescope Fraction[Phase]=
0.05

~ Dimensionless
~ |

Current Phase[Phase]=
Current to Future Phase[Phase]*Current to Past Phase[Phase]*Effect of Percent Complete on Project End\
[Phase]
~ Dimensionless
~ To determine if a design phase is a Current Phase (equals 1), multiply the \
Current to Future Phase indicator times the Current to Past Phase \
indicator...if equals 0, the phase is not yet started (Current to Future \
Phase is 0) or already over (Current to Phase is 0)
|

Percent Complete at Project End[Phase]=
0.8,0.9,0.9,0.95,0.95
~ Dimensionless
~ |

Effect of Percent Complete on Project End f(
[(0,0)-(1,1)],(0,1),(0.999,1),(1,0))
~ Dimensionless
~ |

Effect of Percent Complete on Project End[Phase]=
Effect of Percent Complete on Project End f(Percent Phase Complete[Phase]/Percent Complete at Project End\
[Phase])
~ Dimensionless
~ |

Internal Error Rate[Phase,Discipline]=
Internal Error Rate f[Phase,Discipline]
~ Tasks/Month
~ The rate of internal Q/A and defective discovery is the probability of a \
defect times the probability of discovering the defect times the minimum \
of tasks available for inspection (completed over the time to detect) and \
the inspector constraint (QA constraint)
|

Max Indicated Completion Date[Phase]=
Indicated Completion Date[Phase,A1]
~ Month
~ |

NAVSEA Participation Nominal Percentage[Phase]=
0.3,0.2,0.2,0.1,0.1
~ Dimensionless
~ The desired manning level of NAVSEA relative to Contractors
|

Personnel Assigned[Phase,Discipline]=
NAVSEA New[Phase,Discipline]+Contractor New[Phase,Discipline]+Contractor Experienced\
[Phase,Discipline]+NAVSEA Experienced
[Phase,Discipline]
~ Manpower

~ Total personnel (NAVSEA and Contracted, novice and experienced with the \
project) assigned to each discipline during a given time of each design \
phase
|

Effect of Available Budget on NAVSEA Percent[Phase]=
Effect of Available Budget on NAVSEA Percent f(Available to Desired Budget[Phase])
~ Dimensionless
~ |

Approval Phase Net=
SUM(Approval Phase[Phase!])
~ Dimensionless
~ |

Planned Annual Funding[Phase]=
3.2e+006,1.5e+007,1.62e+007,6.44e+007,2.14e+007
~ Dollars
~ Initial Values determined from DDG-51 program (NAVSEA Ship Design \
Histories and Acquisition Budget results)
|

GettingFatigued[Phase,Discipline]=
(Overtime[Phase,Discipline] - Fatigue[Phase,Discipline]) / TimeToGetFatigued
~ fraction / Month
~ |

Net Review[Phase]=
SUM(Review[Phase,Discipline!])
~ Tasks
~ |

Effect of Approval Phase on Desired Manpower f(
[(0,0)-(1,1)],(0,1),(1,0.5))
~ Dimensionless
~ |

Effect of Approval Phase on NAVSEA Percent[Phase]=
Effect of Approval Phase on NAVSEA Percent f(Approval Phase[Phase])
~ Dimensionless
~ |

Effect of Approval Phase on NAVSEA Percent f(
[(0,0)-(1,2)],(0,1),(1,1.25))
~ Dimensionless
~ |

Available to Desired Budget[Phase]=
IF THEN ELSE(Perceived Funding Requirements[Phase]<=0,4,Available Budget[Phase]/Perceived Funding Requirements\
[Phase])
~ Dimensionless
~ |

Effect of Available Budget on Contractors f(

[(0,0)-(8,10)],(0,0),(0.5,0.2),(0.75,0.5),(1,1),(2,4),(3.86707,6.71053),(6,8),(8,8))
~ Manpower
~ For available budget fractions near 0 (available is low) the fraction of \
contractors to be hired is directly proportional...as available to need is \
very large, more contractors will be hired up to a very large portion \
(overfunding) at which contractors are released\!\!\!
|

Effective Personnel Level[Phase,Discipline]=
(Contractor Experienced[Phase,Discipline]*PDY Contractor Experienced Factor+Contractor New [Phase,Discipline]*PDY Contractor New Factor+NAVSEA Experienced[Phase,Discipline]*PDY NAVSEA Experience Factor\
+NAVSEA New
[Phase,Discipline]*PDY NAVSEA New Factor)*Overtime[Phase,Discipline]
~ Manpower
~ The effective personnel level is the sum of the effective number of \
personnel assigned (number of personnel times an experience factor)
|

Overtime f(
[(0,0)-(2,2.6)],(0,1),(0.175258,1),(0.417526,1),(0.747423,1),(1,1),(1.25,1),(1.5,1.2\
),(1.7,1.4),(1.8,1.6),(1.9,1.8),(2,2))
~ fraction
~ |

Funding Gap[Phase]=
Perceived Funding Requirements[Phase]-Available Budget[Phase]
~ Dollars
~ |

Fiscal Reset=
IF THEN ELSE(Fiscal Counter=12,Fiscal Counter/TIME STEP,0)
~ Dimensionless
~ |

Net Approved[Phase]=
SUM(Approved[Phase,Discipline!])
~ Tasks
~ |

Change to Budget[Phase]=
Current Phase[Phase]*Funding Gap[Phase]/Time to Change Budget
~ Dollars/Month
~ |

Net Completed[Phase]=
SUM(Completed[Phase,Discipline!])
~ Tasks
~ |

Contractors Phase[Phase]=
SUM(Contractor Experienced[Phase,Discipline!])+SUM(Contractor New[Phase,Discipline!]\
)
~ Manpower
~ |

Desired Manpower Phase[Phase]=
SUM(Adjusted Desired Manpower[Phase,Discipline!])
~ Manpower
~ |

NAVSEA Phase[Phase]=
SUM(NAVSEA Experienced[Phase,Discipline!])+SUM(NAVSEA New[Phase,Discipline!])
~ Manpower
~ |

Contractor New Desired Release[Phase,Discipline]=
IF THEN ELSE(-Manpower Shortage[Phase,Discipline]>0,MAX(0, ABS(Manpower Shortage[Phase\
,Discipline])*(1-NAVSEA Participation Adjusted Percentage[Phase,Discipline])*(ABS(1\
-Effect of Available Budget on Contractors[Phase]))),0)
~ Manpower
~ When personnel supluses exist, new contractors are released based as the \
fraction of manpower shortage desired as contractors
|

Review Error Rate[Phase,Discipline]=
Review Error Rate f[Phase,Discipline]
~ Tasks/Month
~ The rate of external Q/A and defective discovery is the probability of a \
defect times the probability of discovering the defect times the minimum \
of tasks available for inspection (reviewed tasks over the time to detect) \
and the inspector constraint (QA constraint)
|

Fiscal Counter Increase=
1
~ Dimensionless
~ |

TimeToGetFatigued = 1
~ Month
~ |

Total Tasks[Phase]=
Net Approved[Phase]+Net Completed[Phase]+Net Review[Phase]+Net TB Coord[Phase]+Net TBD\
[Phase]+Net WIP[Phase]
~ Tasks
~ |

Net TB Coord[Phase]=
SUM(TBCoord[Phase,Discipline!])
~ Tasks
~ |

Net TBD[Phase]=
SUM(TBD[Phase,Discipline!])
~ Tasks
~ |

Net WIP[Phase]=

SUM(WIP[Phase,Discipline!])
~ Tasks
~ |

Fatigue[Phase,Discipline]= INTEG (
GettingFatigued[Phase,Discipline],
1)
~ fraction
~ |

Contractor New Assignments[Phase,Discipline]=
MAX(0,Effect of Available Budget on Contractors[Phase]*Manpower Shortage[Phase,Discipline\
]*(1-NAVSEA Participation Adjusted Percentage[Phase,Discipline]))
~ Manpower
~ Assignments will occur as the Manpower Shortage times the fraction of \
non-NAVSEA personnel required times a factor for budget available
|

Effect of Available Budget on Contractors[Phase]=
Effect of Available Budget on Contractors f(Available to Desired Budget[Phase])
~ Manpower
~ |

Fiscal Counter= INTEG (
Fiscal Counter Increase-Fiscal Reset,
0)
~ Month
~ |

Perceived Funding Requirements[Phase]=
Total Contractors Assigned[Phase]*Contactor Cost*Current Phase[Phase]*ABS(Max Indicated
Completion Date
[Phase]-Time)
~ Dollars
~ |

Program Budget Rate[Phase]=
Annual Funding[Phase]*Current Phase[Phase]/Funding Period
~ Dollars/Month
~ |

Effect of Schedule Gap on Desired Manpower f(
[(-40,0)-(40,10)],(-24,0.25),(-12,0.5),(0,1),(3,1.25),(12,2),(24,4))
~ Dimensionless
~ |

Manpower Shortage[Phase,Discipline]=
Adjusted Desired Manpower[Phase,Discipline]-Personnel Assigned[Phase,Discipline]
~ Manpower
~ |

Contract Establishment Rate[Phase,Discipline]=
Percentage of RFP Contracts[Phase]*Contractor Pool[Phase,Discipline]/Contracting with RFP Rate\
[Phase,Discipline]+(1-Percentage of RFP Contracts[Phase])*Contractor Pool[Phase,Discipline\
]/Contracting with Existing NAVSEA Contracts[Phase,Discipline]

~ Manpower/Month
~ |

minimumCompletionDuration=
1
~ Month
~ |

NAVSEA New Assignments[Phase,Discipline]=
IF THEN ELSE(Manpower Shortage[Phase,Discipline]>0,Manpower Shortage[Phase,Discipline\
]*NAVSEA Participation Adjusted Percentage[Phase,Discipline],0)
~ Manpower
~ For existing manpower shortage, the assigment of NAVSEA Personnel is the \
desired fraction of NAVSEA personnel times the required personnel
|

Schedule Gap[Phase,Discipline]=
Indicated Completion Date[Phase,Discipline]-Desired Schedule[Phase,Discipline]
~ Month
~ |

NAVSEA Exp Desired Release[Phase,Discipline]=
IF THEN ELSE(NAVSEA New Desired Release[Phase,Discipline]<0,0,MAX(0,NAVSEA New Desired Release\
[Phase,Discipline]-NAVSEA New[Phase,Discipline]))
~ Manpower
~ When NAVSEA personnel are being released (NAVSEA New Desired Release is \
positive) experienced personnel are released only after all new personnel \
have been released
|

DesiredAccomplishingRate[Phase,Discipline]=
Perceived TBD[Phase,Discipline] / Remaining Design Phase Duration[Phase,Discipline]
~ Tasks/Month
~ |

Remaining Design Phase Duration[Phase,Discipline]=
MAX(minimumCompletionDuration, Desired Schedule[Phase,Discipline] - Time)
~ Month
~ |

NAVSEA New Desired Release[Phase,Discipline]=
IF THEN ELSE(Manpower Shortage[Phase,Discipline]>0,0,NAVSEA Participation Adjusted Percentage\
[Phase,Discipline]*ABS(Manpower Shortage[Phase,Discipline]))
~ Manpower
~ |

Percentage of RFP Contracts[Phase]=
0.01,0.1,0.2,0.8,0.9
~ Dimensionless
~ The average fraction of total contracts which are RFP's vice existing \
NAVSEA contracts
|

Effect of Schedule Gap on Desired Manpower[Phase,Discipline]=

Effect of Schedule Gap on Desired Manpower f(Schedule Gap[Phase,Discipline])
~ Dimensionless
~ |

Contractor Exp Desired Release[Phase,Discipline]=
IF THEN ELSE(Contractor New Desired Release[Phase,Discipline]<0,0,MAX(0,Contractor New Desired Release\
[Phase,Discipline]-Contractor New[Phase,Discipline]))
~ Manpower
~ |

Contractor Release Period=
1
~ Month
~ Time required to release personnel from the current project is
|

Contractors Available[Phase,Discipline]= INTEG (
Contractor Experience Release Rate[Phase,Discipline]+Contractor New Released[Phase,Discipline\
]-Contracted Assign Rate[Phase,Discipline]+Contract Establishment Rate[Phase,Discipline\
],
0)
~ Manpower
~ |

NAVSEA Experience Gain Period[Phase]=
6
~ Month
~ Months required for individuals to acquire full working knowledge of the \
current project
|

NAVSEA Release Period=
1
~ Month
~ Time required to release personnel from the current project is
|

Contractor New[Phase,Discipline]= INTEG (
Contracted Assign Rate[Phase,Discipline]-Contractor Experience Gain Rate[Phase,Discipline\
]-Contractor New Released[Phase,Discipline],
0)
~ Manpower
~ |

EffectOfFatigueOnProductivity[Phase,Discipline]=
EffectOfFatigueOnProductivity f(Fatigue[Phase,Discipline])
~ dmnl
~ |

Contracting with Existing NAVSEA Contracts[Phase,Discipline]=
3
~ Month
~ Months required to negotiate design work through existing NAVSEA Contracts
|

Contracting with RFP Rate[Phase,Discipline]=
18
~ Month
~ Months required to negotiate design work through new (RFP-request for \
proposals) contracts
|

PDY Contractor Experienced Factor=
1.1
~ Dimensionless
~ Contractor Experienced Personnel have an increased productivity of 20% \
greater than that of an average designer
|

Contractor Baseline Personnel[Phase,Discipline]=
50
~ Manpower
~ NAVSEA Personnel available for assignment to the project by discipline and \
phase
|

Contractor Experience Gain Period[Phase]=
6
~ Month
~ Months required for individuals to acquire full working knowledge of the \
current project
|

Contractor Experience Gain Rate[Phase,Discipline]=
Contractor New[Phase,Discipline]/Contractor Experience Gain Period[Phase]
~ Manpower/Month
~ The rate of transfer of personnel from new to project to experienced with \
the project is the number of personnel over the average time to acquire \
experience
|

Contractor Experienced[Phase,Discipline]= INTEG (
Contractor Experience Gain Rate[Phase,Discipline]-Contractor Experience Release Rate\
[Phase,Discipline],
0)
~ Manpower
~ The accumulation of NAVSEA personnel with direct experience with the \
current design Project is 0 plus the rate of experience gain less the \
release rate of experienced personnel from the project
|

Indicated Completion Date[Phase,Discipline]=
Current Phase[Phase]*(Time+IF THEN ELSE(Estimated Comp Rate[Phase,Discipline]<=0,60,\
Perceived TBD[Phase,Discipline]/Estimated Comp Rate
[Phase,Discipline]))
~ Month
~ The estimated months to completion (per discpline per phase) is 0 if the \
phase is inactive (either passed or not yet started) or is the TBD divided \
by the current rate of completion (personnel by personnel \

productivity)...note at phase start, no personnel are assigned so an \
artificial estimate of 60 months is set.
|

Contractor Pool[Phase,Discipline]= INTEG (
-Contract Establishment Rate[Phase,Discipline],
Contractor Baseline Personnel[Phase,Discipline])
~ Manpower
~ The pool of available contractors not available because contracts are not \
yet in place to allow their use
|

PDY NAVSEA Experience Factor=
1.1
~ Dimensionless
~ NAVSEA Experienced Personnel have an increased productivity of 20% greater \
than that of an average designer
|

EffectOfFatigueOnProductivity f(
[(0,0)-(4,4)],(0,1),(1.2,1.01),(1.5,1.5),(2,2),(3,2.1))
~ dmnl
~ |

EffectOfScheduleGapOnProductivity f(
[(-10,0)-(10,1.75)],(-10,0.75),(0,0.9),(0.757732,0.904605),(1,1),(1.5,1.1),(2.50755,\
1.25877),(3.83686,1.52741),(5,1.684),(10,1.75))
~ dmnl
~ |

PDY NAVSEA New Factor=
0.85
~ Dimensionless
~ NAVSEA Personnel new to the project have an increased productivity of 20% \
less than that of an average designer
|

Estimated Comp Rate[Phase,Discipline]=
Avg Design Rate[Phase,Discipline]*Personnel Assigned[Phase,Discipline]
~ Tasks/Month
~ |

PDY Contractor New Factor=
0.85
~ Dimensionless
~ Contractor Personnel new to the project have a productivity of 20% less \
than that of an average designer
|

Spending Rate[Phase]=
Total Contractors Assigned[Phase]*Contactor Cost
~ Dollars/Month
~ |

Desired Tasks to Assign[Phase,Discipline]=

Personnel Assigned[Phase,Discipline]*Net Productivity Rate[Phase,Discipline]*Design Phase Duration\
[Phase]
~ Tasks
~ The desired number of tasks to be assigned (by discipline) at a given time \
in a phase is the number of personnel available to work times the \
effective productivity of those personnel times months number of months \
into the project
|

Design Phase Duration[Phase]= INTEG (
Design Phase Time Step[Phase],
0)
~ Month
~ From the start of a design phase, how many months have passed...
|

Design Phase Time Measure=
1
~ Month
~ The basic measurement of design duration is 1 month of time
|

Design Phase Time Step[Phase]=
Current Phase[Phase]*Design Phase Time Measure/Design Phase Time Measure
~ Month/Month
~ The rate of increase of the design duration for a current phase (Current \
Phase equals 1) is the current model time step over the basic measurement \
of time (1 month)
|

Assign Rate[Phase,Discipline]=
MIN(TBD[Phase,Discipline]/Assign Period,Desired Tasks to Assign[Phase,Discipline]/Assign Period\
)
~ Tasks/Month
~ The assignment rate is the minimum of the assignable task constraint (TBD \
over assignment period) and the desired task assignment constraint \
(desired tasks for assignment over the assignment period)
|

Release Rate[Phase,Discipline]=
Baseline Tasking[Phase,Discipline]*Current Phase[Phase]/TIME STEP
~ Tasks/Month
~ At the commencement of a design phase, all baseline tasks are released to \
TBD for assignmenet to designers, the release is dependent on the phase \
becoming active...time step is used to provide the release in a single \
pulse.
|

Time to Detect Errors[Phase]=
1
~ Month
~ The minimum time (by phase) required to detect an error in a task
|

Current to Future Phase[Concept]=

1 ~~|
Current to Future Phase[Preliminary]=
Effect of Percent Phase Complete on Current to Future f(Percent Phase Complete[Concept\
]/Percent Phase Complete Desired[Concept]) ~~|
Current to Future Phase[Contract]=
Effect of Percent Phase Complete on Current to Future f(Percent Phase Complete[Preliminary\
]/Percent Phase Complete Desired[Preliminary]) ~~|
Current to Future Phase[Lead Ship]=
Effect of Percent Phase Complete on Current to Future f(Percent Phase Complete[Contract\
]/Percent Phase Complete Desired[Contract]) ~~|
Current to Future Phase[Manufacturing]=
Effect of Percent Phase Complete on Current to Future f(Percent Phase Complete[Lead Ship\
]/Percent Phase Complete Desired[Lead Ship])
~ Dimensionless
~ A design phase can start (equals 1) when the previous design phase ratio \
of completed/approved tasks to desired approved tasks is greater than 1 \
(by the Effect of Percent Phase Complete function.)
|

WIP[Phase,Discipline]= INTEG (
Assign Rate[Phase,Discipline]+Coord Rate[Phase,Discipline]-Comp Rate[Phase,Discipline\
],
0)
~ Tasks
~ Work is progress is the number of tasks released from initial work (assign \
rate) plus the rework tasks returning from coordination (coord rate) less \
the tasks completed by designers (comp rate)
|

Net Comp Rate=
SUM(Comp Rate[Concept,Discipline!])+SUM(Comp Rate[Preliminary,Discipline!])+SUM(Comp Rate\
[Contract,Discipline!])+SUM(Comp Rate
[Lead Ship,Discipline!])+SUM(Comp Rate[Manufacturing,Discipline!])
~ Tasks/Month
~ |

Approval Phase[Phase]=
Approval Phase Effect f(Approval Ratio Actual[Phase]/Approval Ratio Desired[Phase])
~ Dimensionless
~ The approval phase is active (1) for actual to desired ratios greater than \
1 and inactive (0) for ratios less than 1
|

Approval Phase Effect f(
[(0,0)-(2,1)],(0,0),(0.75,0),(0.999,0),(1,1),(2,1))
~ Dimensionless
~ The approval Phase Effect Function compares the ratio of Approval Ratio \
Actual to Desired, for net ratios greater than 1, the approval phase is \
active (1) for ratio less than 1 the approval phase is not active (0)
|

Approval Ratio Actual[Phase]=
(SUM(Approved[Phase,Discipline!])+SUM(Review[Phase,Discipline!]))/SUM(Initial Tasks[\
Phase,Discipline!])
~ Dimensionless

~ The Ratio of total tasks available for or already approved to the total \
intial tasks is the total of tasks released at review and those residing \
as Approved divided by the initial tasks...by phase.

|

Completed[Phase,Discipline]= INTEG (
+Comp Rate[Phase,Discipline]-Review Rate[Phase,Discipline]-Internal Error Rate[Phase\
,Discipline]-Design Spiral Rate[Phase,
Discipline],
0)
~ Tasks
~ Completed tasks are increased by the completion rate (Comp Rate) and \
decreased by release of tasks for NAVSEA review (Review Rate), rework of \
tasks due to concurrent feedback (Design Feedback Rate) and rework due to \
discovered errors (Defective Rate)

|

Approve Rate[Phase,Discipline]=
Approval Phase[Phase]*(Review[Phase,Discipline]/Approval Period[Phase])
~ Tasks/Month
~ The rate of approval of tasks by DoN/DoD is the indicator that tasks \
levels will support approval process (Approval Phase equals 1) times the \
approval rate (reviewable tasks over the time required to review a task)

|

Effect of Percent Phase Complete on Current to Future f(
[(0,0)-(2,1)],(0,0),(0.999,0),(1,1),(2,1))
~ Dimensionless
~ |

Effect of Percent Phase Complete on Current to Past f(
[(0,0)-(2,1)],(0,1),(0.999,1),(1,0),(2,0))
~ Dimensionless
~ |

Comp Rate[Phase,Discipline]=
Comp Rate f[Phase,Discipline]
~ Tasks/Month
~ The rate of completion of tasks is the average completion rate for tasks \
(...see resource sector for first order control of comp rate)

|

TBD[Phase,Discipline]= INTEG (
-Assign Rate[Phase,Discipline]+Release Rate[Phase,Discipline]+Rescope Rate[Phase,Discipline\
],
0)
~ Tasks
~ TBD is the quantity of tasks available for assignment increased by release \
(at phase start) and by rescoping of the project (design change \
introduction) by authorities, TBD is decreased by the assignment rate \
(assigning tasks to designers)

|

Current to Past Phase[Concept]=
Effect of Percent Phase Complete on Current to Past f(Current to Future Phase[Preliminary\

]) ~~|
Current to Past Phase[Preliminary]=
Effect of Percent Phase Complete on Current to Past f(Current to Future Phase[Contract\
]) ~~|
Current to Past Phase[Contract]=
Effect of Percent Phase Complete on Current to Past f(Current to Future Phase[Lead Ship\
]) ~~|
Current to Past Phase[Lead Ship]=
1 ~~|
Current to Past Phase[Manufacturing]=
1
~ Dimensionless
~ A phase is finished (equals 0) when the next design phase has achieved an \
indicator value (Current to Future Phase) for phase initiation (equals \
1)...achieved through the table function Effect of Percent complete.
|

TBCoord[Phase,Discipline]= INTEG (
+Design Spiral Rate[Phase,Discipline]-Coord Rate[Phase,Discipline]+Internal Error Rate\
[Phase,Discipline]+Review Error Rate[Phase,Discipline],
0)
~ Tasks
~ The tasks requiring coordination prior to rework are increased by the \
tasks requiring rework (design feedback rate, defective rate and reject \
rate) less those tasks completing coordination and returning to the work \
cycle (coord rate)
|

NAVSEA Baseline Personnel[Phase,Discipline]=
7
~ Manpower
~ NAVSEA Personnel available for assignment to the project by discipline and \
phase
|

Desired Schedule[Phase,Discipline]= INTEG (
Schedule Shift[Phase,Discipline],
Initial Schedule Projection[Phase])
~ Month
~ The Desired Schedule is the initial schedule (months to phase completion \
from project start) estimate for each phase increased (or decreased) by \
the rate of schedule shift
|

Perceived TBD[Phase,Discipline]=
Current Phase[Phase]*MAX(0,Initial Tasks[Phase,Discipline]*Percent Phase Complete Desired\
[Phase]-Perceived Completed[Phase,Discipline])
~ Tasks
~ The perceived TBD (for an active phase as determined by the boolean \
Current Phase) is the maximum of 0 (floor value) and the tasks required to \
close the phase (initial tasks times transition ratio) minus the perceived \
completed tasks.
|

Net Personnel Assigned=

SUM(Net Personnel Assigned Phase[Phase!])
~ Manpower
~ Net Personnel Assigned (by project) is the sum of personnel assigned by \
phase
|

Annual Funding[Phase]= INTEG (
Change to Budget[Phase],
Planned Annual Funding[Phase])
~ Dollars
~ |

Net Perceived TBD[Phase]=
SUM(Perceived TBD[Phase,Discipline!])
~ Tasks
~ Net Perceived TBD (by phase) is the sum of TBD by design discipline
|

Effect of Available Budget on NAVSEA Percent f(
[(0,0)-(1,1)],(0,1),(0.05,1),(0.1,0.9),(0.2,0.75),(1,0.75))
~ Dimensionless
~ |

Available Budget[Phase]= INTEG (
-Spending Rate[Phase]+Program Budget Rate[Phase],
1)
~ Dollars
~ |

Coord Rate f[Phase,Discipline]=
TBCoord[Phase,Discipline]/Average Coord Period[Phase,Discipline]
~ Tasks/Month
~ Average Coordination Rate is the Tasks available for coordination over the \
time required to coordinate a task
|

Coord Rate[Phase,Discipline]=
Coord Rate f[Phase,Discipline]
~ Tasks/Month
~ The rate of coordination of tasks is the average coordination rate for \
tasks (...see resource sector for first order control of coord rate)
|

Net Coord Rate[Phase]=
SUM(Coord Rate f[Phase,Discipline!])
~ Tasks/Month
~ |

Time to Change Budget=
36
~ Month
~ |

Contactor Cost=
6597

~ Dollars/(Month*Manpower)
~ The average monthly cost per contractor, including overhead costs, in FY96 \
dollars
|

Spent Budget[Phase]= INTEG (
Spending Rate[Phase],
0)
~ Dollars
~ |

NAVSEA Assign Period=
1
~ Month
~ |

Time to Shift Schedule=
24
~ Month
~ |

Perceived Completed[Phase,Discipline]=
Review[Phase,Discipline]+Completed[Phase,Discipline]+Approved[Phase,Discipline]
~ Tasks
~ Perceived completed is the number of tasks in review plus those awaiting \
review (completed) plus those approved
|

Contractor Assign Period[Phase]=
1
~ Month
~ |

Net Perceived Completed[Phase]=
SUM(Perceived Completed[Phase,Discipline!])
~ Tasks
~ Net perceieved completed tasks (by phase) are the sum of all perceived \
completed tasks by design discipline
|

Net Personnel Assigned Phase[Phase]=
SUM(Personnel Assigned[Phase,Discipline!])
~ Manpower
~ Net Current Personnel Assigned (by phase) is the sum of personnel assigned \
by design discipline
|

Step Down Time=
0
~ Month
~ |

Pink Noise = INTEG(Change in Pink Noise,0)
~ Dimensionless
~ Pink Noise is first-order autocorrelated noise. Pink noise provides a realistic \

noise input to
models in which the next random shock depends in part on the previous \
shocks. The user
can specify the correlation time. The mean is 0 and the standard deviation \
is specified
by the user.
|

Input=
MAX(Pink Noise,MIN(STEP(Step Height,Step Up Time)+
(Pulse Quantity/TIME STEP)*PULSE(Pulse Time,TIME STEP)+
RAMP(Ramp Slope,Ramp Start Time,Ramp End Time)+
Sine Amplitude*SIN(2*3.14159*Time/Sine Period)+
STEP(1,Noise Start Time)*Pink Noise,1-STEP(Step Height,Step Down Time)))
~ Dimensionless
~ Input is a dimensionless variable which provides a variety of test input patterns, \
including a step,
pulse, sine wave, and random noise.
|

Change in Pink Noise = (White Noise - Pink Noise)/Noise Correlation Time
~ 1/Month
~ Change in the pink noise value; Pink noise is a first order exponential smoothing \
delay of the white
noise input.
|

Sine Amplitude=
1
~ Dimensionless
~ Amplitude of sine wave in customer orders (fraction of mean).
|

Sine Period=
25
~ Month
~ Period of sine wave in customer demand. Set initially to 50 weeks (1 \
year).
|

Step Height=
1
~ Dimensionless
~ Height of step input to customer orders, as fraction of initial value.
|

Pulse Quantity=
1
~ Month
~ The quantity to be injected to customer orders, as a fraction of the base value of \
Input.
For example, to pulse in a quantity equal to 50% of the current value of \
input, set to
.50.
|

```
Pulse Time=
        62
        ~       Month
        ~       Time at which the pulse in Input occurs.
        |

White Noise = Noise Standard Deviation*((24*Noise Correlation Time/TIME STEP)^0.5*(RANDOM 0 1\
                () - 0.5
))
        ~       Dimensionless
        ~       White noise input to the pink noise process.
        |

Noise Correlation Time = 4
        ~       Month
        ~       The correlation time constant for Pink Noise.
        |

Ramp Slope=0
        ~       1/Month
        ~       Slope of the ramp input, as a fraction of the base value (per week).
        |

Ramp Start Time=
        0
        ~       Month
        ~       Start time for the ramp input.
        |

Ramp End Time=1e+009
        ~       Month
        ~       End time for the ramp input.
        |

Noise Standard Deviation=
        0.5
        ~       Dimensionless
        ~       The standard deviation of the pink noise process.
        |

Noise Start Time=
        0
        ~       Month
        ~       Start time for the random input.
        |

Step Up Time=
        0
        ~       Month
        ~       Time for the step input.
        |

Approved[Phase,Discipline]= INTEG (
        Approve Rate[Phase,Discipline],
```

0)
~ Tasks
~ The total tasks (by discipline) approved by DoN/DoD and considered removed \
from the phase
|

Total Approved Tasks[Phase]=
SUM(Approved[Phase,Discipline!])
~ Tasks
~ The total approved tasks for all disciplines in a single design phase
|

Approval Period[Phase]=
1,1,1,0.125,0.125
~ Month
~ The current time required to review a task by DoN/DoD is considered 3 \
months
|

Approval Ratio Desired[Phase]=
0.8, 0.9, 0.95, 0.5, 0.5
~ Tasks/Tasks
~ |

Review[Phase,Discipline]= INTEG (
Review Rate[Phase,Discipline]-Approve Rate[Phase,Discipline]-Review Error Rate[Phase\
,Discipline],
0)
~ Tasks
~ The tasks reviewed by NAVSEA are increased by the review rate and \
decreased by those tasks rejected to rework (errors discovered) and those \
design tasks provided to DoN/DoD for final approval
|

Baseline Tasking[Phase,Discipline]= INTEG (
-Release Rate[Phase,Discipline],
Initial Tasks[Phase,Discipline])
~ Tasks
~ The Initial Stock of design tasks for the 23 design disciplines and 5 \
phases, the stock is drained to 0 at the commencement of each phase (the \
phase becomes active.) This stock initiates the model for a phase
|

Percent Phase Complete Desired[Phase]=
0.8, 0.9, 0.95, 0.75, 0.5
~ Tasks/Tasks
~ |

Phase:
Concept, Preliminary, Contract, Lead Ship, Manufacturing
~ Tasks/Tasks
~ |

Assign Period=
1

```
	~	Month
	~	The average time required to assign a task is 1 month
	|

Discipline:
	A1, A2, A3, B1, B2, B3, B4, B5, C1, C2, C3, C4, C5, C6, C7, D1, D2, D3, D4, D5, E1, \
		E2, F1
	~
	~		|

Feedback:
	A1, A2, A3, B1, B2, B3, B4, B5, C1, C2, C3, C4, C5, C6, C7, D1, D2, D3, D4, D5, E1, \
		E2, F1
	~
	~		|

Initial Tasks[Concept,Discipline]=
	8, 8, 12, 2, 1, 1, 4, 2, 4, 6, 2, 1, 2, 7, 5, 3, 2, 2, 2, 1, 3, 2, 3 ~~|
Initial Tasks[Preliminary,Discipline]=
	10, 8, 13, 2, 3, 2, 5, 4, 4, 19, 2, 1, 11, 15, 16, 8, 7, 7, 12, 7, 9, 5, 4 ~~|
Initial Tasks[Contract,Discipline]=
	13, 8, 13, 2, 4, 2, 5, 4, 4, 20, 2, 2, 11, 18, 16, 9, 8, 8, 14, 7, 10, 5, 6 ~~|
Initial Tasks[Lead Ship,Discipline]=
	41, 25, 39, 6, 14, 9, 15, 12, 12, 60, 6, 6, 33, 54, 54, 35, 24, 24, 42, 21, 30, 15, \
		18 ~~|
Initial Tasks[Manufacturing,Discipline]=
	14, 9, 13, 2, 5, 3, 5, 4, 4, 20, 2, 2, 11, 18, 20, 12, 8, 8, 14, 7, 10, 5, 6
	~	Tasks
	~	The baseline number of total deliverable tasks for each of the 23 design \
		disciplines for each of the five design phases...values determined from \
		DDG-51 Design Histories and evaluations from the Laverghetta Design Thesis
	|

Review Period[Phase]=
	0.325,0.325,0.325,0.1,0.1
	~	Month
	~	Minimum time required to review a single task
	|

Design Spiral Matrix[A1,Discipline]=
	0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0 ~~|
Design Spiral Matrix[A2,Discipline]=
	1, 0, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1 ~~|
Design Spiral Matrix[A3,Discipline]=
	1, 1, 0, 1, 1, 1, 0, 1, 1, 0, 0, 0, 1, 1, 0, 1, 1, 1, 1, 1, 1, 1, 1 ~~|
Design Spiral Matrix[B1,Discipline]=
	1, 1, 0, 0, 0, 1, 1, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0 ~~|
Design Spiral Matrix[B2,Discipline]=
	1, 1, 0, 1, 0, 1, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0 ~~|
Design Spiral Matrix[B3,Discipline]=
	1, 1, 0, 0, 1, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 1 ~~|
Design Spiral Matrix[B4,Discipline]=
	1, 1, 0, 0, 0, 0, 0, 1, 1, 1, 0, 0, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 0 ~~|
Design Spiral Matrix[B5,Discipline]=
	1, 1, 0, 1, 1, 0, 1, 0, 0, 0, 0, 0, 0, 0, 1, 1, 0, 1, 1, 0, 0, 0, 1 ~~|
```

Design Spiral Matrix[C1,Discipline]=
1, 1, 0, 0, 1, 1, 0, 0, 0, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 0, 0, 0, 1 ~~|
Design Spiral Matrix[C2,Discipline]=
1, 1, 0, 0, 1, 1, 1, 0, 0, 0, 0, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1 ~~|
Design Spiral Matrix[C3,Discipline]=
1, 1, 0, 0, 0, 0, 1, 0, 0, 0, 0, 1, 0, 0, 0, 1, 1, 0, 0, 0, 0, 0, 0 ~~|
Design Spiral Matrix[C4,Discipline]=
1, 1, 0, 0, 0, 0, 1, 0, 0, 1, 0, 0, 0, 1, 0, 0, 0, 0, 0, 1, 1, 0, 0 ~~|
Design Spiral Matrix[C5,Discipline]=
1, 1, 0, 1, 1, 1, 1, 0, 0, 1, 1, 1, 0, 1, 1, 1, 1, 1, 1, 0, 0, 0, 1 ~~|
Design Spiral Matrix[C6,Discipline]=
1, 1, 0, 1, 1, 1, 1, 0, 0, 1, 0, 0, 0, 0, 1, 0, 0, 0, 0, 0, 0, 0, 1 ~~|
Design Spiral Matrix[C7,Discipline]=
1, 1, 0, 1, 1, 1, 1, 1, 0, 1, 0, 0, 0, 1, 0, 1, 1, 1, 1, 1, 1, 1, 1 ~~|
Design Spiral Matrix[D1,Discipline]=
1, 1, 0, 1, 1, 1, 1, 1, 0, 1, 0, 0, 0, 1, 1, 0, 1, 1, 1, 1, 0, 0, 1 ~~|
Design Spiral Matrix[D2,Discipline]=
1, 1, 0, 1, 1, 1, 1, 1, 0, 1, 1, 0, 1, 1, 1, 1, 0, 1, 1, 0, 0, 0, 1 ~~|
Design Spiral Matrix[D3,Discipline]=
1, 1, 0, 1, 1, 1, 1, 1, 0, 1, 0, 0, 0, 1, 1, 1, 1, 0, 1, 1, 1, 1, 1 ~~|
Design Spiral Matrix[D4,Discipline]=
1, 1, 0, 1, 1, 1, 1, 1, 0, 1, 0, 1, 1, 1, 1, 1, 1, 1, 0, 1, 1, 1, 1 ~~|
Design Spiral Matrix[D5,Discipline]=
1, 1, 0, 1, 1, 1, 1, 1, 0, 1, 0, 0, 0, 1, 1, 1, 0, 1, 1, 0, 0, 0, 1 ~~|
Design Spiral Matrix[E1,Discipline]=
1, 1, 0, 1, 1, 1, 1, 1, 0, 1, 0, 0, 0, 1, 1, 1, 0, 1, 1, 0, 0, 1, 1 ~~|
Design Spiral Matrix[E2,Discipline]=
1, 1, 0, 1, 1, 1, 1, 1, 0, 1, 1, 0, 0, 1, 1, 1, 0, 1, 1, 0, 1, 0, 1 ~~|
Design Spiral Matrix[F1,Discipline]=
1, 1, 0, 0, 0, 0, 0, 0, 1, 1, 0, 0, 0, 1, 1, 1, 1, 1, 1, 1, 1, 1, 0
~ Tasks/Tasks
~ The design spiral matrix (aka design structure matrix) represents the \
first order input/output requirements associating one ship design \
discipline to another...a value of "0" indicates the discipline is not an \
input to the given element, "1" indicates a significant level of input to \
the element
|

Min Comp Period[Phase,Discipline]=
0.5
~ Month
~ Minimum period of time required to complete any given task regardless of \
the resources available is estimated to be one week (same for all tasks \
and all phases)
|

Average Coord Period[Phase,Discipline]=
1
~ Month
~ For tasks requiring coordination and personnel interaction, this is the \
average period required to coordinate a task

Feedback Fraction[Phase]=
0.5
~ Tasks/Tasks

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